



ATLAS OF STRUCTURAL GEOLOGY

Soumyajit Mukherjee

Atlas of Structural Geology

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Preface

Documentation of structures in different scales is the first step in many structural geological studies. This edited atlas gives an overview of diverse structures. Due to lack of space or inappropriateness, sometimes interesting structural snaps cannot be published in journals. This book fills that gap.

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Chapter 1

Folds

KEYWORDS

Folds; Folds not related to shear zones; Overturned fold; Shear zone related fold; Sheath fold; Superposed fold.

Two of the most intensely studied aspects in structural geology are morphology and genesis of folds (see Ramsay, 1967; Hudleston and Lan, 1993; Ez, 2000; Harris et al., 2002; Harris, 2003; Alsop and Holdsworth, 2004; Mandal et al., 2004; Carreras et al., 2005; Bell, 2010; Hudleston and Treagus, 2010; Godin et al., 2011; Harris et al., 2012a,b; Llorens et al., 2013; Mukherjee et al., in press). Of particular importance is whether folds found inside ductile shear zones are related to ductile shear (e.g., Mandal et al., 2004; Carreras et al., 2005; Bell, 2010). This chapter presents folds of different geometries and generations, some related with ductile shear zones, from different scales (Figures 1.1–1.87).

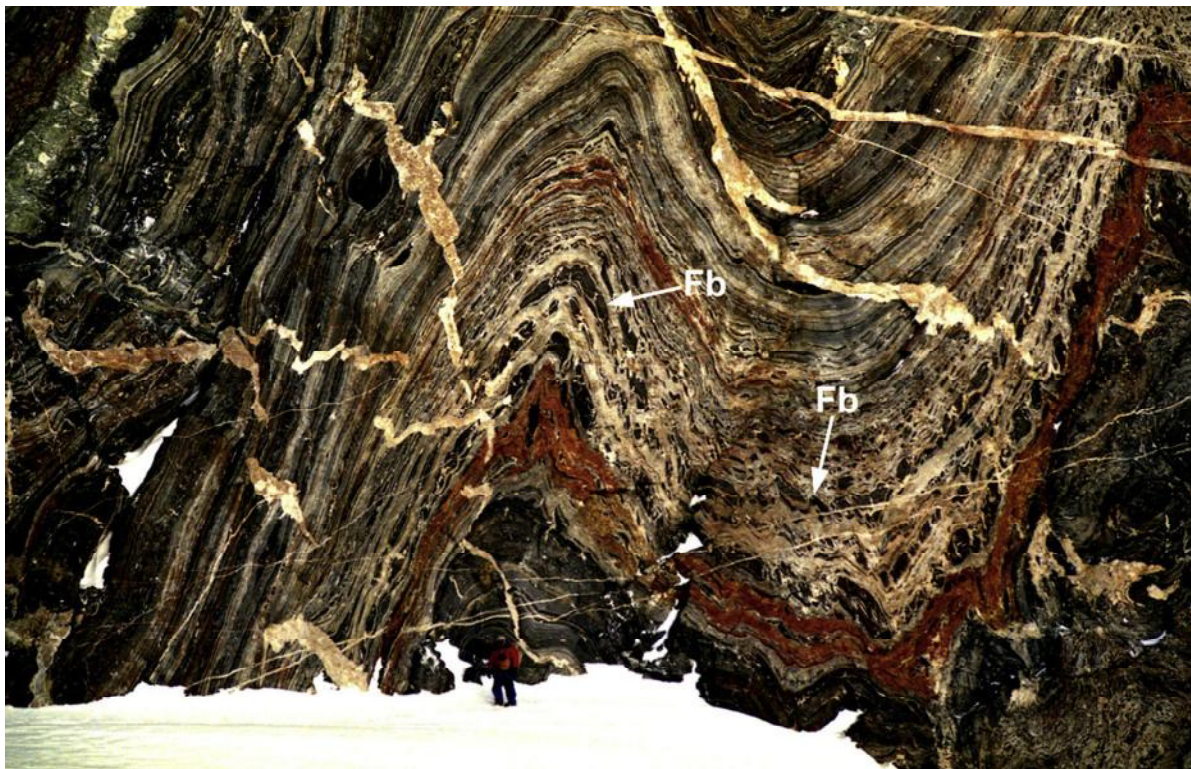


FIGURE 1.1 Upright folds and folded boudins resulting from continental collision of East and West Gondwana. The boudins of dark-colored amphibolite (Fb) in light-colored biotite-hornblende gneiss have originally pancake shapes with flattening parallel to compositional layering of gneiss, and resulted from the layer-parallel extension and thinning of crustal rocks within 640–600 Ma (Toyoshima et al., 1995). The folds with wavelengths of 20–30 m are parasitic upright folds of larger-scale upright fold related to 600–560 Ma sinistral transpression and crustal shortening during the collision (Toyoshima et al., 2013). The boudins (Fb) folded by the parasitic folds suggest that the tectonic regime changed from layer-normal to layer-parallel compression (Toyoshima et al., 2013). Osanai et al. (2013) presented SHRIMP U–PB ages for metamorphic rocks from the Sør Rondane Mountains, East Antarctica, and recognized periods of ultrahigh-temperature metamorphism (pre-main metamorphic stage) during 750–700 Ma and granulite- to amphibolite-facies metamorphism during 640–600 Ma. Location: 72°09'42"S, 25°31'50"E, the southern part of Salen in the Sør Rondane Mountains, East Antarctica. (Tsuyoshi Toyoshima, Masaaki Owada, Kazuyuki Shiraiishi)

REFERENCES

- Acharyya, S.K., Saha, P., 2008. Geological setting of the Siang Dome located at the Eastern Himalayan Syntaxis. *Himalayan Journal of Science* 5, 16–17.
- Alsop, G.I., Holdsworth, R.E., 2004. Shear zone folds: records of flow perturbation or structural inheritance? In: Alsop, G.I., Holdsworth, R.E., McCaffey, K.J.W., Hand, M. (Eds.), *Flow Processes in Faults and Shear Zones*, vol. 224. Geol Soc London, Spec Publ, pp. 177–199.
- Anderson, J.R., Payne, J.L., Kelsey, D.E., Hand, M., Collins, A.S., Santosh, M., 2012. High-pressure granulites at the dawn of the Proterozoic. *Geology* 40, 431–434.
- Bell, T.H., 2010. Deformation partitioning, foliation successions and their significance for orogenesis: hiding lengthy deformation histories in mylonites. In: Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M., Strachan, R.A. (Eds.), *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne*, vol. 335. Geol Soc London, Spec Publ, pp. 275–292.
- Bell, T.H., Rudenach, M.J., 1983. Sequential porphyroblast growth and crenulation cleavage development during progressive deformation. *Tectonophysics* 92, 171–194.
- Bikramaditya Singh, R.K., Gururajan, N.S., 2011. Microstructures in quartz and feldspars of the Bomdila gneiss from western Arunachal Himalaya, India: Implications for geotectonic evolution of the Bomdila mylonitic zone. *Journal of Asian Earth Sciences* 42, 1163–1178.
- Calamita, F., Pizzi, A., Ridolfi, M., Rusciadelli, G., Scisciani, V., 1998. Il buttressing delle faglie normali sinsedimentarie pre-thrusting sulla strutturazione neogenica della catena appenninica: l'esempio della M.gna dei Fiori (Appennino Centrale esterno). *Bollettino Della Società Geologica Italiana* 117, 725–745.
- Calamita, F., Ben M'Barek, M., Di Vincenzo, M., Pelorosso, M., 2004. The Pliocene thrust system of the Gran Sasso salient (Central Apennines, Italy). In: Pasquarè, G., Venturini, C. (Eds.), *Mapping Geology in Italy*. S.EL.CA, Florence, Italy, pp. 227–234.
- Calamita, F., Esestime, P., Paltrinieri, W., Scisciani, V., Tavarnelli, E., 2009. Structural inheritance of pre- and syn- orogenic normal faults on the arcuate geometry of Pliocene-Quaternary thrusts: examples from the Central and Southern Apennine Chain. *Italian Journal of Geosciences* 128, 381–394.
- Calamita, F., Satolli, S., Scisciani, V., Esestime, P., Pace, P., 2011. Contrasting styles of fault reactivation in curved orogenic belts: examples from the Central Apennines (Italy). *Geological Society of America Bulletin* 123, 1097–1111.
- Calamita, F., Pace, P., Satolli, S., 2012a. Coexistence of fault-propagation and fault-bend folding in curve-shaped foreland fold-and-thrust belts: examples from the Northern Apennines (Italy). *Terra Nova* 24, 396–406.
- Carreras, J., Druguet, E., Griera, A., 2005. Shear zone-related folds. *Journal of Structural Geology* 27, 1229–1251.
- Chetty, T.R.K., 1996. Proterozoic shear zones in southern granulite terrain, India. In: Santosh, M., Yoshida, M. (Eds.), *Gondwana Research Group Memoir-3: The Archaean and Proterozoic Terrains in Southern India within East Gondwana*, pp. 77–89.
- Chetty, T.R.K., Bhaskar Rao, Y.J., 2006a. The Cauvery Shear Zone, southern Granulite Terrain, India: a crustal-scale flower structure. *Gondwana Research* 10, 77–85.
- Chetty, T.R.K., Bhaskar Rao, Y.J., 2006b. Constrictive deformation in transpressional regime: field evidence from the Cauvery Shear Zone, southern Granulite Terrain, India. *Journal of Structural Geology* 28, 713–720.
- Collins, A.S., Clark, C., Plavsa, D., 2014. Peninsular India in Gondwana: The tectonothermal evolution of the Southern Granulite terrain and its Gondwanan counterparts. *Gondwana Research* 25, 190–203.
- Crowe, W.A., Nash, C.R., Harris, L.B., Leeming, P.M., Rankin, L.R., 2003. The geology of the Rengali Province: implications for the tectonic development of northern Orissa, India. *Journal of Asian Earth Sciences* 21, 697–710.
- Decandia, F.A., Tavarnelli, E., Alberti, M., 2002. Pressure-solution fabrics and their overprinting relationships within a minor fold train of the Umbria-Marche Apennines, Italy. *Bollettino Della Società Geologica Italiana* 1, 687–694.
- Deng, H., Zhang, C., Koyi, H.A., 2013. Identifying the characteristic signatures of fold-accommodation faults. *Journal of Structural Geology* 56, 1–19.
- Drury, S.A., Holt, R.W., 1980. The tectonic framework of the south Indian Craton, a reconnaissance involving Landsat imagery. *Tectonophysics* 65, T1–T15.
- Dyni, J.R., Hawkins, J.E., 1981. Lacustrine turbidites in the Green river formation, northwestern Colorado. *Geology* 9, 235–238.
- Ez, V., 2000. When shearing is a cause of folding. *Earth-Science Reviews* 51, 155–172.
- Fagereng, A., Sibson, R.H., 2010. Melange rheology and seismic style. *Geology* 38, 751–754.
- Ghosh, S.K., Mandal, N., Khan, D., Deb, S.K., 1992. Modes of superposed buckling in single layers controlled by initial tightness of early folds. *Journal of Structural Geology* 14, 381–394.
- Ghosh, S.K., 1993. *Structural Geology: Fundamentals and Modern Developments*. Pergamon Press, Oxford.
- Ghosh, S.K., Hazra, S., Sengupta, S., 1999. Planar, non-planar and refolded sheath folds in Phulad shear zone, Rajasthan, India. *Journal of Structural Geology* 21, 1715–1729.
- Ghosh, J.G., de Wit, M.J., Zartman, R.E., 2004. Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrain of India, with implications for Gondwana Studies. *Tectonics* 23, TC3006.
- Godin, L., Yakymchuk, C., Harris, L.B., 2011. Himalayan hinterland-verging superstructure folds related to foreland-directed infrastructure ductile flow: Insights from centrifuge analogue modeling. *Journal of Structural Geology* 33, 329–342.
- Gopalakrishnan, K., 1994. An overview of Southern Granulite Terrain, India—Constraints in Reconstruction of Precambrian Assembly of Gondwanaland, vol. 2, Oxford and IBH Publication, Gondwana Nine, pp.1003–1026.
- Grasemann, B., Martel, S., Passchier, C., 2005. Reverse and normal drag along a fault. *Journal of Structural Geology* 27, 999–1010.
- Harris, L.B., 2003. Folding in high-grade rocks due to back-rotation between shear zones. *Journal of Structural Geology* 25, 223–240.
- Harris, L.B., Godin, L., Yakymchuk, C., 2012a. Regional shortening followed by channel flow induced collapse: a new mechanism for—dome and keel geometries in Neoproterozoic granite-greenstone terrains. *Precambrian Research* 212–213, 139–154.

- Harris, L.B., Koyi, H.A., Fossen, H., 2002. Mechanisms for folding of high-grade rocks in extensional tectonic settings. *Earth-Science Reviews* 59, 163–210.
- Harris, L.B., Yakymchuk, C., Godin, L., 2012b. Implications of centrifuge simulations of channel flow for opening out or destruction of folds. *Tectonophysics* 526–529, 67–87.
- Hemmann, M., 1972. Ausbildung und Genese des Leinesteinsalzes und des Hauptanhydrits (Zechstein 3) im Ostteil des Subherzynen Beckens. *Ber. deutsch. Ges. Geol. Wiss. B. Min. Lagerstättenf* 16, 307–411.
- Hibbard, M.J., 1995. Petrography to petrogenesis. Chapter 21 “Metamorphic Rocks”. Prentice-Hall, New Jersey. 587 p.
- Hobbs, B.E., Means, W.D., Williams, P.F., 1976. *An Outline of Structural Geology*. John Wiley & Sons, New York.
- Hudleston, P.J., Lan, L., 1993. Information from fold shapes. *Journal of Structural Geology* 15, 253–264.
- Hudleston, P.J., Treagus, S.H., 2010. Information from folds. a review. *Journal of Structural Geology* 32, 2042–2071.
- Johnson, R.C., 1981. Preliminary Geologic Map of the Desert Gulch Quadrangle, Garfield County, Colorado. U.S. Geological Survey Miscellaneous Field Investigations Map MF-1328, scale 1:24,000.
- Khanal, S., Robinson, D.M., Mandal, S., Simkhada, P., 2014. Structural, geochronological and geochemical evidence for two distinct thrust sheets in the ‘Main Central thrust zone’, the Main Central thrust and Ramgarh–Munsiari thrust: implications for upper crustal shortening in central Nepal. In: Mukherjee, S., Carosi, R., van der Beek, P.A., Mukherjee, B.K., Robinson, D.M. (Eds.), *Tectonics of the Himalaya*. Special Publications, Geological Society, London, 412. <http://dx.doi.org/10.1144/SP412.2>.
- Kronenberg, A.K., Kirby, S.H., Pinkstone, J., 1990. Basal slip and mechanical anisotropy of biotite. *Journal of Geophysical Research* 95, 257–278.
- Lin, A., 1997. Ductile deformation of biotite in foliated cataclastite, Iida-Matsukawa fault, central Japan. *Journal of Asian Earth Sciences* 15, 407–411.
- Llorens, M.-G., Bons, P.D., Griera, A., Gomez-Rivas, E., Evans, L.A., 2013. Single layer folding in simple shear. *Journal of Structural Geology* 50, 209–220.
- Mortimer, N., 2004. New Zealand’s geological foundations. *Gondwana Research* 7, 261–272.
- Mandal, N., Samanta, S.K., Chakraborty, C., 2004. Problem of folding in ductile shear zones: a theoretical and experimental investigations. *Journal of Structural Geology* 26, 475–489.
- Marco, S., Agnon, A., 1995. Prehistoric earthquake deformations near Masada, Dead Sea graben. *Geology* 23, 695–698.
- Mitra, S., 2002. Fold-accommodation faults. *AAPG Bulletin* 86, 671–693.
- McClay, K.R., Insley, M.W., 1986. Duplex structures in the Lewis thrust sheet. Crowsnest Pass, Rocky mountains, Alberta, Canada. *Journal of Structural Geology* 8, 911–922.
- Montenat, C., Barrier, P., Ott d’Estevou, P., Hibsche, C., 2007. Seismites: an attempt at critical analysis and classification. *Sedimentary Geology* 196, 5–30.
- Mukherjee S., 2007. *Geodynamics, Deformation and Mathematical Analysis of Metamorphic Belts of the NW Himalaya*. (Unpublished Ph.D. thesis). Indian Institute of Technology Roorkee. pp. 1–267.
- Mukherjee, S., 2010. Microstructures of the Zaskar shear zone. *Earth Science India* 3, 9–27.
- Mukherjee, S., 2011a. Flanking microstructures of the Zaskar shear zone, west Indian Himalaya. *YES Bulletin* 1, 21–29.
- Mukherjee, S., 2011b. Estimating the viscosity of rock Bodies—a comparison between the Hormuz and the Namakdan salt diapirs in the Persian Gulf, and the Tso Moriri gneiss dome in the Himalaya. *Journal of Indian Geophysical Union* 15, 161–170.
- Mukherjee, S., 2013. *Deformation Microstructures in Rocks*. Springer.
- Mukherjee, S., 2014a. *Atlas of Shear-Zone Structures in Meso-scale*. Springer.
- Mukherjee, S., 2014b. Review of the flanking structures in meso- and micro-scales. *Geological Magazine* 151, 957–974.
- Mukherjee, S., Koyi, H.A., 2009. Flanking microstructures. *Geological Magazine* 146, 517–526.
- Mukherjee, S., Koyi, H.A., 2010. Higher Himalayan Shear Zone, Zaskar Indian Himalaya- microstructural studies and extrusion mechanism by combination of simple shear and channel flow. *International Journal of Earth Sciences* 99, 1083–1110.
- Mukherjee, S., Puneekar, J.N., Mahadani, T., Mukherjee, R. Intrafolial folds- review & examples from the western Indian Higher Himalaya. In: Mukherjee S., Mulchrone K.F. (Eds.), *Ductile Shear Zones: From Micro- to Macro-scales*. Wiley-Blackwell, in press.
- Mukherjee, S., Talbot, C.J., Koyi, H.A., 2010. Viscosity estimates of salt in the Hormuz and Namakdan salt diapirs, Persian Gulf. *Geological Magazine* 147, 497–507.
- Mukhopadhyay, B., Bose, M.K., 1994. Transitional granulite-eclogite facies metamorphism of basic supracrustal rocks in a shear zone complex in the Precambrian shield of south India. *Mineralogical Magazine* 58, 97–118.
- Nelson, K.D., 1982. A suggestion for the origin of mesoscopic fabric in accretionary mélangé, based on features observed in the Chrystalls Beach Complex, South Island, New Zealand. *Geological Society of America Bulletin* 93, 625–634.
- Osanai, Y., Nogi, Y., Baba, S., Nakano, N., Adachi, T., Hokada, T., Toyoshima, T., Owada, M., 2013. Geologic evolution of the Sør Rondane Mountains, East Antarctica: collision tectonics proposed based on metamorphic processes and magnetic anomalies. *Precambrian Research* 234, 8–29.
- Passchier, C.W., Trouw, R.A.J., 1996. *Microtectonics*. Springer-Verlag. p. 289.
- Passchier, C., 2001. Flanking structures. *Journal of Structural Geology* 23, 951–9962.
- Passchier, C., Trouw, R., 2005. *Microtectonics*. Chapter 4 “Foliations, Lineations and Lattice Preferred Orientation”. Springer, Berlin. 336 p.
- Passchier, C., Trouw, R., 2005. *Microtectonics*. Chapter 7 “Porphyroblasts and Reaction Rims”. Springer, Berlin. p. 336.
- Praveen, M.N., Santosh, M., Yang, Q.Y., Zhang, Z.C., Huang, H., Singaneni, S., Sajinkumar, K.S., 2014. Zircon U–Pb geochronology and Hf isotope of felsic volcanics from Attappadi, India: Implications for Neoproterozoic convergent margin tectonics. *Gondwana Research* 26, 907–924.
- Ramsay, J.G., 1967. *Folding and Fracturing of Rocks*. McGraw Hill, New York. pp. 117, 352, 390, 413, 414.

- Ramsay, J.G., Huber, M.I., 1987. *The Techniques of Modern Structural Geology. Folds and Fractures*, vol. 2, Academic Press, London, Orlando, San Diego, New York, Austin, Boston, Sydney, Tokyo, Toronto. 391 pp.
- Rodríguez-Pascua, M.A., Calvo, J.P., De Vicente, G., Gómez-Gras, D., 2000. Soft-sediment deformation structures interpreted as seismites in lacustrine sediments of the Prebetic Zone, SE Spain, and their potential use as indicators of earthquake magnitudes during the Late Miocene. *Sedimentary Geology* 135, p. 117–135.
- Saito, Y., Tsunogae, T., Santosh, M., Chetty, T.R.K., Horie, K., 2011. Neoproterozoic high pressure metamorphism from the northern margin of the Palghat–Cauvery suture zone, southern India: petrology and zircon SHRIMP geochronology. *Journal of Asian Earth Sciences* 40, 268–285.
- Santosh, M., Maruyama, S., Sato, K., 2009. Anatomy of a Cambrian suture in Gondwana: Pacific-type orogeny in southern India? *Gondwana Research* 16, 321–341.
- Santosh, M., Tsunogae, T., Koshimoto, S., 2004. First report of sapphirine-bearing rocks from the Palghat–Cauvery shear zone system, southern India. *Gondwana Research* 7, 620–626.
- Santosh, M., Xiao, W.J., Tsunogae, T., Chetty, T.R.K., Yellappa, T., 2012. The Neoproterozoic subduction complex in southern India: SIMS zircon U–Pb ages and implications for Gondwana assembly. *Precambrian Research* 190–208.
- Satolli, S., Speranza, F., Calamita, F., 2005. Paleomagnetism of the Gran Sasso range salient (central Apennines, Italy): pattern of orogenic rotations due to translation of a massive carbonate indenter. *Tectonics* 24, TC4019.
- Schmalholz, S.M., Podladchikov, Y.Y., 2001. Strain and competence contrast estimation from fold shape. *Tectonophysics* 340, 195–213.
- Scisciani, V., Tavarnelli, E., Calamita, F., 2002. The interaction of extensional and contractional deformations in the outer zones of the Central Apennines, Italy. *Journal of Structural Geology* 24, 1647–1658.
- Séguret M., 1972. *Etude tectonique des nappes et séries décollées de la partie centrale du versant sud des Pyrénées* (Ph.D. thesis). Caractère synsédimentaire, rôle de la compression et de la gravité. University of Montpellier.
- Sengupta, S., Ghosh, S.K., 2004. Analysis of transpressional deformation from geometrical evolution of mesoscopic structures from Phulad Shear Zone, Rajasthan, India. *Journal of Structural Geology* 26, 1961–1976.
- Sengupta, S., Ghosh, S.K., Deb, S.K., Khan, D., 2005. Opening and closing of folds in superposed deformations. *Journal of Structural Geology* 27, 1282–1299.
- Sengupta, S., Ghosh, S.K., 2007. Origin of striping lineation and transposition of linear structures in shear zones. *Journal of Structural Geology* 29, 273–287.
- Strozyk, F., van Gent, H., Urai, J.L., Kukla, P.A., 2012. 3D seismic study of complex intra-salt deformation: an example from the Zechstein 3 stringer in the western Dutch offshore. In: Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T., Hodgkinson, R. (Eds.), *Salt Tectonics, Sediments and Prospectivity*, vol. 363, Geological Society, London, pp. 489–501. Special Publications.
- Tānavsuu-Milkeviciene, K., Sarg, F.J., 2012. Evolution of an organic-rich lake basin – stratigraphy, climate and tectonics: Piceance Creek basin, Eocene Green River Formation. *Sedimentology* 59, 1735–1768.
- Tavarnelli, E., 1996. The effects of pre-existing normal faults on thrust ramp development: an example from the northern Apennines, Italy. *Geologische Rundschau* 85, 363–371.
- Tavarnelli, E., 1997. Structural evolution of a foreland fold-and-thrust belt: the Umbria-Marche Apennines, Italy. *Journal of Structural Geology* 19, 523–534.
- Tavarnelli, E., Decandia, F.A., Renda, P., Tramutoli, M., Gueguen, E., Alberti, M., 2001. Repeated reactivation in the Apennine-Maghrebide system, Italy: a possible example of fault-zone weakening? In: Holdsworth, R.E., Strachan, R.A., Magloughlin, J.F., Knipe, R.J. (Eds.), *The Nature and Tectonic Significance of Fault Zone Weakening*, vol. 186, Geological Society, London, pp. 273–286. Special Publication.
- Ternet, Y., Baudin, T., Laumonier, B., Barnolas, A., Gil-Peña, I., Martín-Alfageme, S., 2008. Mapa Geológico de los Pirineos a E. 1: 400.000. IGME–BRGM. Madrid-Orleans.
- Törő, B., Pratt, B.R., Renaut, R.W., 2013. Seismically Induced Soft-sediment Deformation Structures in the Eocene Lacustrine Green River Formation (Wyoming, Utah, Colorado, USA) – a Preliminary Study. *GeoConvention2013: Integration*, Calgary (Poster abstract).
- Toyoshima, T., Owada, M., Shiraishi, K., 1995. Structural evolution of metamorphic and intrusive rocks from the central part of the Sør Rondane Mountains, East Antarctica. *Proceedings of the NIPR Symposium on Antarctic Geosciences* 8, 75–97.
- Toyoshima, T., Osanai, Y., Baba, S., Hokada, T., Nakano, N., Adachi, T., Otsubo, M., Ishikawa, M., Nogi, Y., 2013. Sinistral transpressional and extensional tectonics in Dronning Maud Land, East Antarctica, including the Sør Rondane Mountains. *Precambrian Research* 234, 30–46.
- Urai, J.L., 1987. Development of microstructure during deformation of carnallite and bischofite in transmitted light. *Tectonophysics* 135, 251–263.
- Van Gent, H., Urai, J.L., de Keijzer, M., 2011. The internal geometry of salt structures – a first look using 3D seismic data from the Zechstein of the Netherlands. *Journal of Structural Geology* 33, 292–311.
- Van Loon, A.J., 2009. Soft-sediment deformation structures in siliciclastic sediments: an overview. *Geologos* 15, 3–55.
- Van Loon, A.J., Brodzikowski, K., Gotowala, R., 1984. Structural analysis of kink bands in unconsolidated sands. *Tectonophysics* 104, 351–374.
- Wang, S., Mo, Y., Phillips, R.J., Wang, C., 2014. Karakoram fault activity defined by temporal constraints on the Ayi Shan detachment, SW Tibet. *International Geology Review* 56, 15–28.
- Williams, M.L., Scheltema, K.E., Jercinovic, M.J., 2001. High-resolution compositional mapping of matrix phases: implications for mass transfer during crenulation cleavage development in the Moretown Formation, western Massachusetts. *Journal of Structural Geology* 23, 923–939.
- Williams-Straud, S.C., Paul, J., 1997. Initiation and growth of gypsum piercement structures in the Zechstein Basin. *Journal of Structural Geology* 19, 897–907.
- Yellappa, T., Chetty, T.R.K., Tsunogae, T., Santosh, M., 2010. The Manamedu Complex: geochemical constraints on Neoproterozoic suprasubduction zone ophiolite formation within the Gondwana suture in southern India. *Journal of Geodynamics* 50, 268–285.
- Yellappa, T., Santosh, M., Chetty, T.R.K., Kwon, S., Park, C., Nagesh, P., Mohanty, D.P., Venkatasivappa, V., 2012. A Neoproterozoic dismembered ophiolite complex from southern India: geochemical and geochronological constraints on its suprasubduction origin. *Gondwana Research* 21, 246–265.

- Yin, A., 2006. Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. *Earth-Science Reviews* 76, 1–131.
- Zeibig, S., Wendzel, J., 2000. Exploration of anhydrite wall and klippe structure for an optimized extraction of rock salt in the K+S salt mine Bernburg (Northern Germany). *World Salt Symposium*, vol. 1, Elsevier, Amsterdam, pp. 193–198.
- Zulauf, G., Zulauf, J., Bornemann, O., Kihm, N., Peinl, M., Zanella, F., 2009. Experimental deformation of a single-layer anhydrite in halite matrix under bulk constriction. Part 1: geometric and kinematic aspects. *Journal of Structural Geology* 31, 460.

Chapter 2

Ductile Shear Zones

KEYWORDS

C-plane; Couette flow; Ductile shear zone; Flanking structure; Mineral fish; Primary shear (C) plane; Pure shear; Shear; Simple shear; Synthetic secondary shear plane.

“Tabular or sheetlike, planar or curvilinear zones in which rocks are more highly strained than rocks adjacent to the zone” are called ductile shear zones (Davis et al., 2012; also see Mukherjee and Biswas, 2014; in press). Identification and study of ductile shear zones (Figures 2.1–2.55) are important since major plate boundaries are defined by such shear zones (Regenauer-Lieb and Yuen, 2003). We need to study such zones since along them partially molten rocks can flow (review by Clark et al., 2011). Secondly, viscous dissipation related to such zones has been investigated (Nabelek et al., 2011). No slip boundary condition was assumed classically to explain kinematics of ductile shear zones (Ramsay 1980; Mukherjee 2012; etc). However, recently, slip boundary condition is more recognized (Frehner et al., 2011; Mulchrone and Mukherjee, submitted). The ductile shear sense/sense of movement from such zones can be deciphered mainly from asymmetric sigmoid, parallelogram and lenticular clasts and intrafolial folds (Lister and Snoke, 1984; ten Grotenhuis et al., 2003; Mukherjee, 2011a,b, 2013a,b,c, 2014a,b,c; Bhadra and Gupta, in press). See Passchier and Trouw (2005) for review on ductile shear zones, and Mukherjee and Mulchrone (2013) and Mulchrone and Mukherjee (in press) for shear heat pattern in these zones. In addition to such shear sense indicators, this chapter also presents near symmetric clasts that form possibly within shear zones but that do not give the shear sense.



FIGURE 2.1 Domino style normal faults with strike slip component, dipping 50° toward $N60^\circ\text{--}64^\circ\text{E}$ (rake 70°W). Upper Pliocene–Lower Pleistocene polymictic volcanic breccias. A transtension component with western extension, is likely due to the parallelism of the Cordillera with the NW-trending Middle America trench located ~ 160 km to the W. The Cordillera de Tilarán is an andesitic extinct volcanic range, a paleoarc genetically associated with the Costa Rica subduction zone. There most of the ongoing and recent maximum and minimum horizontal stress are generated. Campos de Oro Arriba ($10^\circ 22' 4.09''\text{N}$ – $84^\circ 54' 57.77''\text{W}$), Guanacaste Province, Costa Rica. See Dabrowski and Graseman (2014) as a latest paper on domino type structure. (Guillermo Alvarado Induni)

REFERENCES

- Bhadra, S., Gupta, S., Banerjee, M., 2004. Structural evolution across the Eastern Ghats Mobile Belt–Bastar Craton boundary, India: hot over cold thrusting in an ancient collision zone. *Journal of Structural Geology* 26, 233–245.
- Bhadra S., Gupta S. Reworking of a basement-cover interface during terrane boundary shearing: an example from the Khariar basin, Bastar Craton, India. In: Mukherjee S., Mulchrone K.F. (Eds.), *Ductile Shear Zones: From Micro- to Macro-scales*. Wiley-Blackwell, in press.
- Bikramaditya Singh, R.K., 2010. Geochemistry and mineral chemistry of granitoids of lesser himalayan crystallines, Western Arunachal Himalaya: implication for petrogenesis. *Journal of the Geological Society of India* 75, 618–631.
- Biswal, T.K., Jena, S.K., Datta, S., Das, R., Khan, K., 2000. Deformation of the terrane boundary shear zone (Lakhna shear zone) between the Eastern Ghats Mobile Belt and the Bastar Craton, in the Balangir and Kalahandi districts of Orissa. *Journal of the Geological Society of India* 55, 367–380.
- Biswal, T.K., DeWaele, B., Ahuja, H., 2007. Timing and dynamics of the juxtaposition of the Eastern Ghats Mobile Belt against the Bhandara Craton, India: a structural and zircon U–Pb SHRIMP study of the fold-thrust belt and associated nepheline syenite plutons. *Tectonics* 26, TC4006.
- Clark, C., Fitzsimons, I.C.W., Healy, D., et al., 2011. How does the Continental crust gets really hot? *Elements* 7, 235–240.
- Crowe, W.A., Nash, C.R., Harris, L.B., Leeming, P.M., Rankin, L.R., 2003. The geology of the Rengali Province: implications for the tectonic development of Northern Orissa, India. *Journal of Asian Earth Sciences* 21, 697–710.
- Dabrowski, M., Graseman, B., 2014. Domino boudinage under layer-parallel simple shear. *Journal of Structural Geology* 68, 58–65.
- Davis, G.H., Reynolds, S.J., Kluth, C.F., 2012. *Structural Geology of Rocks and Regions*. Wiley, New York.
- Dobmeier, C., Raith, M., 2003. Crustal architecture and evolution of the Eastern Ghats Belt and adjacent regions of India. In: Yoshida, M., Windley, B.F., Dasgupta, S. (Eds.), *Proterozoic East Gondwana: Supercontinent Assembly and Breakup*, vol. 206. Geological Society of London, Special Publications, pp. 145–168.
- Dutta, A., Gupta, S., Panigrahi, M.K., 2010. The southern Rengali province – a reworked or exotic terrane? *Indian Journal of Geology* 80, 81–96.
- Engelder, T., Marshak, S., 1985. Disjunctive cleavage formed at shallow depths in sedimentary rocks. *Journal of Structural Geology* 7, 327–343.
- Fagereng, A., Remitti, F., Sibson, R.H., 2010. Shear veins observed along planar anisotropy at high angles to greatest compressive stress. *Nature Geoscience* 3, 482–485.
- Fagereng, A., Remitti, F., Sibson, R.H., 2011. Incrementally developed slickenfibres – geological record of repeating low stress-drop seismic events? *Tectonophysics* 510, 381–386.
- Frehner, M., Exner, U., Mancktelow, N.S., Grujic, D., 2011. The not-so-simple effects of boundary conditions on models of simple shear. *Geology* 39, 719–722.
- Fujimoto, Y., Yamamoto, M., 2010. On the granitoids in the Shirakami mountains and correlation to the Cretaceous to Paleogene granitoids distributed in the Northeast Japan. *Earth Science* 64, 127–144 (in Japanese with English abstract).
- Ghosh, S.K., 1993. *Structural Geology: Fundamentals and Modern Developments*. Pergamon Press, Oxford. p. 598.
- Ghosh, S.K., Hazra, S., Sengupta, S., 1999. Planar, non-planar and refolded sheath folds in Phulad shear zone, Rajasthan, India. *Journal of Structural Geology* 21, 1715–1729.
- Grimmer, J.C., Glodny, J., Drüppel, K., Greiling, R.O., Kontny, A., 2015. Early- to mid-Silurian extrusion wedge tectonics in the central Scandinavian Caledonides. *Geology* 43, 347–350.
- Grimmer, J.C., Greiling, R.O., Gerdes, A., 2011. The Ammarnäs complex in the central Scandinavian Caledonides: an allochthonous basin fragment in the Sveconorwegian foreland? *Terra Nova* 23, 270–279.
- ten Grotenhuis, S.M., Trouw, R.A.J., Passchier, C.W., 2003. Evolution of mica fish in mylonite rocks. *Tectonophysics* 372, 1–21.
- Hada, S., Ito, M., Landis, C.A., Cawood, P., 2001. Large-scale translation of accreted terranes along continental margins. *Gondwana Research* 4, 628–629.
- Harayama, S., Takahashi, Y., Nakano, S., Kariya, Y., Komazawa, M., 2000. Geology of the Tateyama District. With Geological Sheet Map at 1:50,000. Geological Survey of Japan. p. 218 (Japanese with English abstract 6 p).
- Kontny, A., Engelmann, R., Grimmer, J.C., Greiling, R.O., Hirt, A., 2012. Magnetic fabric development in a highly anisotropic magnetite-bearing ductile shear zone (Seve Nappe Complex, Scandinavian Caledonides). *International Journal of Earth Sciences* 101, 671–692.
- Koyi, H.A., Schmeling, H., Burchardt, S., Talbot, C., Mukherjee, S., Sjöström, H., 2013. Shear zones between rock units with no relative movement. *Journal of Structural Geology* 50, 82–90.
- Lister, G.S., Snoke, A.W., 1984. S-C mylonites. *Journal of Structural Geology* 6, 617–638.
- Mancktelow, N.S., Pennacchioni, G., 2005. The control of precursor brittle fracture and fluid-rock interaction on the development of single and paired ductile shear zones. *Journal of Structural Geology* 27, 645–661.
- Mancktelow, N.S., Pennacchioni, G., 2013. Late magmatic healed fractures in granitoids and their influence on subsequent solid-state deformation. *Journal of Structural Geology* 57, 81–96.
- Miklavič, B., Rožič, B., 2008. The onset of Maastrichtian basinal sedimentation on Mt. Matajur, NW Slovenia. *RMZ – Materials and Geoenvironment* 55, 199–214.
- Mukherjee, S., 2007. Geodynamics, deformation and mathematical analysis of metamorphic belts of the NW Himalaya. Unpublished Ph.D. thesis Indian Institute of Technology Roorkee 1–267.
- Mukherjee, S., 2010a. Structures at Meso- and Micro-scales in the Sutlej section of the Higher Himalayan Shear Zone in Himalaya. *e-Terra* 7, 1–27.
- Mukherjee, S., 2010b. Microstructures of the Zanskar shear zone. *Earth Science India* 3, 9–27.
- Mukherjee, S., 2011a. Flanking microstructures of the Zanskar shear zone, West Indian Himalaya. *YES Bulletin* 1, 21–29.
- Mukherjee, S., 2011b. Mineral fish: their morphological classification, usefulness as shear sense indicators and genesis. *International Journal of Earth Sciences* 100, 1303–1314.

- Mukherjee, S., 2012. Simple shear is not so simple! Kinematics and shear senses in Newtonian viscous simple shear zones. *Geological Magazine* 149, 819–826.
- Mukherjee, S., 2013a. *Deformation Microstructures in Rocks*. Springer.
- Mukherjee, S., 2013b. Higher Himalaya in the Bhagirathi section (NW Himalaya, India): its structures, backthrusts and extrusion mechanism by both channel flow and critical taper mechanism. *International Journal of Earth Sciences* 102, 1851–1870.
- Mukherjee, S., 2013c. Channel flow extrusion model to constrain dynamic viscosity and Prandtl number of Higher Himalayan Shear Zone. *International Journal of Earth Sciences* 102, 1811–1835.
- Mukherjee, S., 2014a. *Atlas of Shear Zone Structures in Meso-scale*. Springer.
- Mukherjee, S., 2014b. Review of flanking structures in Meso- and Micro-scales. *Geological Magazine* 151, 957–974.
- Mukherjee, S., 2014c. Mica inclusions inside host mica grains from the Sutlej section of the Higher Himalayan Crystallines, India: Morphology and Constrains in Genesis. *Acta Geologica Sinica* 88, 1729–1741.
- Mukherjee, S., Biswas, R., 2014. Kinematics of horizontal simple shear zones of concentric arcs (Taylor–Couette flow) with incompressible Newtonian rheology. *International Journal of Earth Sciences* 103, 597–602.
- Mukherjee S, Biswas, R. Biviscous horizontal simple shear zones of concentric arcs (Taylor Couette flow) with incompressible Newtonian rheology. In: Mukherjee S, Mulchrone K.F (Eds.), *Ductile Shear Zones: From Micro- to Macro-scales*. Wiley-Blackwell, in press.
- Mukherjee, S., Koyi, H.A., 2009. Flanking microstructures. *Geological Magazine* 146, 517–526.
- Mukherjee, S., Koyi, H.A., 2010a. Higher Himalayan Shear Zone, Sutlej section: structural geology and extrusion mechanism by various combination of simple shear, pure shear and channel flow in shifting modes. *International Journal of Earth Sciences* 99, 1267–1303.
- Mukherjee, S., Koyi, H.A., 2010b. Higher Himalayan Shear Zone: Zaskar Indian Himalaya-Microstructural studies and extrusion mechanism by a combination of simple shear and channel flow. *International Journal of Earth Sciences* 99, 1267–1303.
- Mukherjee, S., Mulchrone, K.F., 2013. Viscous dissipation pattern in incompressible Newtonian simple shear zones: an analytical model. *International Journal of Earth Sciences* 102, 1165–1170.
- Mukherjee, S., Puneekar, J.N., Mahadani, T., Mukherjee, R. Intrafolial folds-review & examples from the western Indian Higher Himalaya. In: Mukherjee S., Mulchrone K.F (Eds.), *Ductile Shear Zones: From Micro- to Macro-scales*. Wiley-Blackwell, in press.
- Mulchrone KF, Mukherjee S. Submitted. Kinematics and shear heat pattern of ductile simple shear zones with ‘slip boundary condition’. *International Journal of Earth Sciences*.
- Mulchrone KF, Mukherjee S. In press. Shear senses and viscous dissipation of layered ductile simple shear zones. *Pure and Applied Geophysics*. <http://dx.doi.org/10.1007/s00024-015-1035-8>.
- Nabelek, P.I., Hofmeister, A.M., Whittington, A.G., 2011. The influence of temperature-dependent thermal diffusivity on the conductive cooling rates of plutons and temperature-time paths in contact aureoles. *Earth and Planetary Science Letters* 317, 157–164.
- Pamplona, J., Rodrigues, B.C., 2011. Kinematic interpretation of shearband boudins: new parameters and ratios useful in HT simple shear zones. *Journal of Structural Geology* 33, 38–50.
- Pamplona, J., Rodrigues, B.C., Fernández, C., 2014. Folding as precursor of asymmetric boudinage in shear zones affecting migmatitic terranes. *Geogaceta* 55, 15–18.
- Passchier, C.W., Simpson, C., 1986. Porphyroclast systems as kinematic indicators. *Journal of Structural Geology* 8, 831–844.
- Passchier, C.W., 2001. Flanking structures. *Journal of Structural Geology* 23, 951–962.
- Passchier, C.W., Trouw, R., 2005. *Microtectonics*, Second ed. Springer, Berlin (Chapter 5, Shear zones, 336 p).
- Pennacchioni, G., Mancktelow, N.S., 2007. Nucleation and initial growth of a shear zone network within compositionally and structurally heterogeneous granulites under amphibolite facies conditions. *Journal of Structural Geology* 29, 1757–1780.
- Platt, J.P., Vissers, R.L.M., 1980. Extensional structures in anisotropic rocks. *Journal of Structural Geology* 2, 397–410.
- Ramsay, J.G., 1980. Shear zone geometry: a review. *Journal of Structural Geology* 2, 83–99.
- Regenauer-Lieb, K., Yuen, D.A., 2003. Modeling shear zones in geological and planetary sciences: solid-and fluid-thermal-mechanical approaches. *Earth- Science Reviews* 63, 295–349.
- Rutter, E.H., 1983. Pressure solution in nature, theory and experiment. *Journal of the Geological Society, London* 140 (5), 725–740.
- Sengupta, S., Ghosh, S.K., 2004. Analysis of transpressional deformation from geometrical evolution of mesoscopic structures from phulad shear zone, Rajasthan, India. *Journal of Structural Geology* 26, 1961–1976.
- Shimizu, I., 1988. Ductile deformation in the low-grade part of the Sanbagawa metamorphic belts in the northern Kanto Mountains, Central Japan. *Journal of Geological Society of Japan* 94, 609–628.
- Shimizu, I., Yoshida, S., 2004. Strain geometries in the Sanbagawa metamorphic belt inferred from deformation structures in metabasite. *Island Arc* 13, 95–109.
- Takahashi, Y., 2002. Granitic mylonites situated around the Shirakami Mountains, Northeast Japan. *Earth Science* 56, 215–216. In Japanese.
- Takahashi, Y., Cho, D.L., Kee, W.S., 2010. Timing of mylonitization in the Funatsu Shear Zone within Hida Belt of southwest Japan: Implications for correlation with the shear zones around the Ogccheon Belt in the Korean Peninsula. *Gondwana Research* 17, 102–115.
- Treagus, S., Lan, L., 2003. Simple shear of deformable square objects. *Journal of Structural Geology* 25, 1993–2005.
- Trouw, R.A.J., Passchier, C.W., Wiersma, D.J., 2010. *Atlas of Mylonites and Related Microstructures*. Springer.
- Vernon, R.H., 2004. *A Practical Guide to Rock Microstructure*. Cambridge University Press. 610 pp.

Chapter 3

Brittle Faults

KEYWORDS

Brittle shear zone; Brittle tectonics; Conjugate faults; Faults; Kinematic indicators; P-plane; Slickensides; Y-plane.

Brittle shear zones/fault zones are usually defined by curved brittle P-planes bound by usually straight Y-planes (Passchier and Trouw, 2005). These shears may affect as a narrow zone within the rock bodies (Misra et al. 2015). Brittle sheared lenses of rocks vary in geometry, and the P-planes may curve only near the Y-planes (Mukherjee, 2014a,b). Fault gouge zones sometimes contain P-planes that help to deduce the shear sense. Fault planes/Y-planes may contain slickensides. See Doblus (1998) for detail of slickenside types and their reliable use in shear sense determination. This is despite Tjia (1964) questioned reliability of slickensides as shear sense indicators. Deformational structures and especially faulted units within soft-sedimentary structures are quite common (Byrne, 1994) (Figures 3.1–3.49). In collisional tectonic regimes, brittle faults can form either in an in-sequence or in an out-of-sequence manner (Mukherjee, in press).

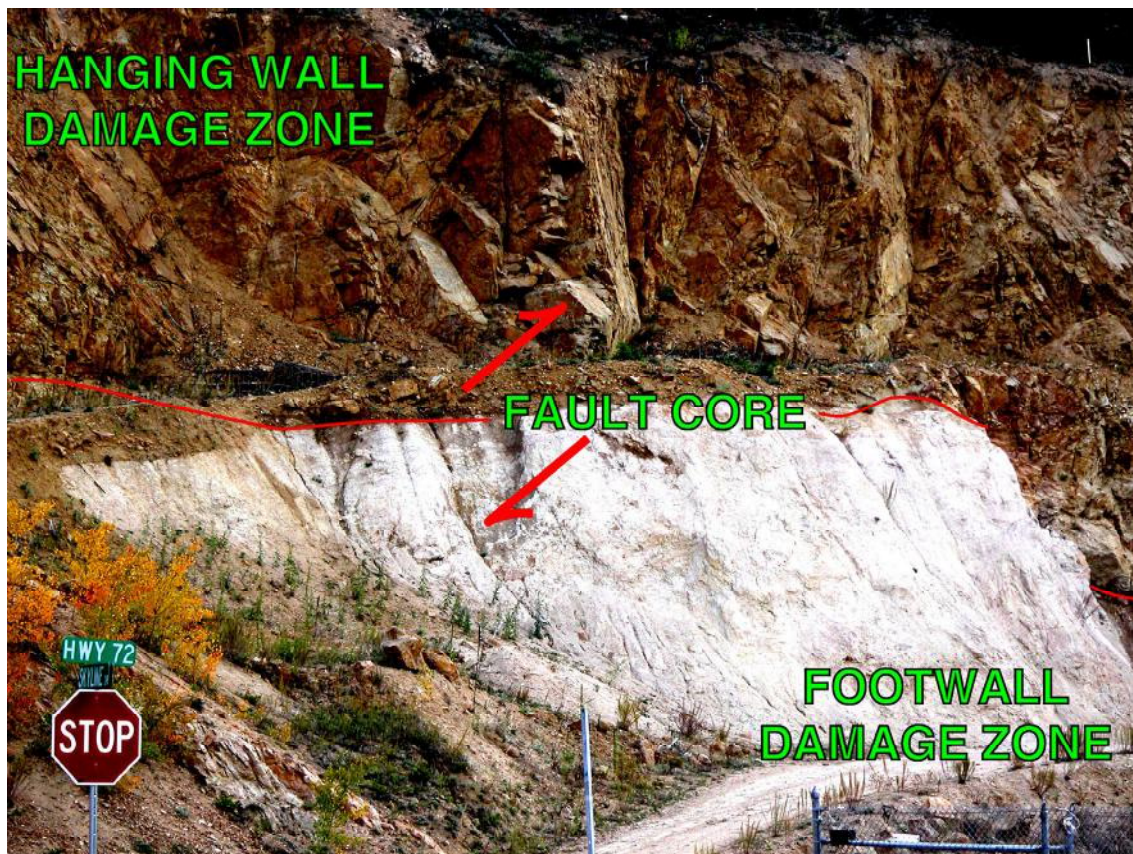


FIGURE 3.1 Road-cut exposure of the Coal Creek fault zone, central eastern Front Range, Colorado, USA ($39^{\circ}54'14''\text{N}$, $105^{\circ}20'46''\text{W}$). This reverse fault zone occurs within the 1.7 Ga Boulder Creek, granodiorite batholith and hosts ~620-m west directed slip. The exposure shows a discrete, clay-rich gouge fault core and surrounding damage zone (cf. Caine et al., 1996). The damage zone is characterized by relatively low-temperature hydrothermal alteration concentrated mainly in hanging wall fractures juxtaposed against the pervasively and moderately altered clay-rich, white footwall. See Caine et al. (2010) for details. (Jonathan Caine)

REFERENCES

- Agard, P., Yamato, P., Jolivet, L., Burov, E., 2009. Exhumation of oceanic blueschists and eclogites in subduction zones: timing and mechanisms. *Earth-Science Reviews* 92, 53–79.
- Andersen, T., Austrheim, H., 2006. Fossil earthquakes recorded by pseudotachylytes in mantle peridotite from the Alpine subduction complex of Corsica. *Earth and Planetary Science Letters* 242, 58–72.
- Andreani, M., Baronnet, A., Boullier, A.M., Gratier, J.P., 2004. A microstructural study of a “crack-seal” type serpentine vein using SEM and TEM techniques. *European Journal of Mineralogy* 16, 585–595.
- Angelier, J., 1984. Tectonic analyses of fault slip data sets. *Journal of Geophysical Research* 89, 5835–5848.
- Austrheim, H., Andersen, T.B., 2004. Pseudotachylytes from Corsica: fossil earthquakes from a subduction complex. *Terra Nova* 16, 193–197.
- Barker, S.L.L., Cox, S.F., Eggins, S.M., Gagan, M.K., 2006. Microchemical evidence for episodic growth of antitaxial veins during fracture-controlled fluid flow. *Earth Planetary Science Letters* 250, 331–344.
- Byrne, T., 1994. Sediment deformation, dewatering and diagenesis: illustrations from selected mélange zones. In: Maltman, A. (Ed.), *The Geological Deformation of Sediments*. Chapman & Hall (Chapter 8), pp. 239–260.
- Calamita, F., Satolli, S., Turtù, A., 2012. Analysis of thrust shear zones in curve-shaped belts: deformation mode and timing of the Olevano-Antrodoco-Sibillini thrust (Central/Northern Apennines of Italy). *Journal of Structural Geology* 44, 179–187.
- Calamita, F., Decandia, F.A., Deiana, G., Fiori, A.P., 1991. Deformation of s-c tectonites in the scaglia cinerea formation in the Spoleto area (South-East Umbria). *Bollettino della Società Geologica Italiana* 110, 661–665.
- Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault Zone Architecture and Permeability Structure. *Geology* 24, 1025–1028.
- Caine, J.S., Ridley, J., Wessel, Z.R., 2010. To reactivate or not to reactivate—Nature and varied behavior of structural inheritance in the proterozoic basement of the eastern Colorado Mineral Belt over 1.7 billion years of earth history. In: Morgan, L.A., Quane, S.L. (Eds.), *Through the Generations: Geologic and Anthropogenic Field Excursions in the Rocky Mountains from Modern to Ancient*. Geological Society of America Field Guide, vol. 18, pp. 119–140.
- Childs, C., Nicol, A., Walsh, J.J., Watterson, J., 1996. The growth of vertically segmented normal faults. *Journal of Structural Geology* 18, 1389–1397.
- Compagnoni, R., Groppo, C., 2006. Gli amianti in Val di Susa e le rocce che li contengono. *Rendiconti della Società Geologica Italiana* 3, 21–28.
- Cowan, H.A., 1991. The North Canterbury earthquake of September 1, 1888. *Journal of the Royal Society of New Zealand* 21, 13–24.
- Deseta, N., Andersen, T.B., Ashwal, L., 2014. A weakening mechanism for intermediate-depth seismicity? Detailed petrographic and microtextural observations from blueschist facies pseudotachylytes, Cape Corse, Corsica. *Tectonophysics* 610, 138–149.
- Doblas, M., 1998. Slickenside kinematic indicators. *Tectonophysics* 295, 187–197.
- El-Wahed, M.A.A., Kamha, S.Z., 2010. Pan-African dextral transpressive duplex and flower structure in the Central Eastern Desert of Egypt. *Gondwana Research* 18, 315–336.
- Federico, L., Crispini, L., Scambelluri, M., Capponi, G., 2007. Different PT paths recorded in a tectonic mélange (Voltri Massif, NW Italy): implications for the exhumation of HP rocks. *Geodinamica Acta* 20, 3–19.
- Fodor, L., Sztanó, O., Kövér, Sz., 2013. Pre-conference field trip: mesozoic deformation of the northern transdanubian range (Gerecse and Vértes Hills). *Acta Mineralogica-Petrographica. Field Guide Series* 31, 1–34.
- Fogarasi, A., 1995. Sedimentation on tectonically controlled submarine slopes of Cretaceous age, Gerecse Mts., Hungary - working hypothesis. *Általános Földtani Szemle* 27, 15–41.
- Greiling, R.O., Garfunkel, Z., Zachrisson, E., 1998. The orogenic wedge in the central Scandinavian Caledonides: Scandian structural evolution and possible influence on the foreland basin. *GFF* 120, 181–190.
- Hancock, P.L., 1985. Brittle microtectonics: principles and practice. *Journal of Structural Geology* 7, 437–457.
- Hirth, G., Tullis, J., 1994. The brittle-plastic transition in experimentally deformed quartz aggregates. *Journal of Geophysical Research: Solid Earth* 99, 11731–11747.
- Hoogerduijn Strating, E.H., Vissers, R.L.M., 1994. Structures in natural serpentinite gouges. *Journal of Structural Geology* 16, 1205–1215.
- Jaroszewski, W., 1984. *Fault and Fold Tectonics* (Translated). J. Wiley & Sons, 565 p.
- Karant, R.V., Gadhave, M.S., 2007. Structural intricacies: emergent thrusts and blind thrusts of central Kachchh, western India. *Current Science* 93, 1271–1280.
- Karkanis, P., 1995. The slip-fiber chrysotile asbestos deposit in the Zidani area, northern Greece. *Ore Geology Reviews* 10, 19–29.
- Katayama, I., Parkinson, C.D., Okamoto, K., Nakajima, Y., Maruyama, S., 2000. Supersiliciclinopyroxene and silica exsolution in UHPM eclogite and pelitic gneiss from the Kokchetav massif, Kazakhstan. *American Mineralogist* 85, 1368–1374.
- Ludman, A., West, D.P., Jr., (Eds.), 1999. *The Norumbega Fault System of the Northern Appalachians*: Geological Society of America Special Paper, 331, 199 p.
- Misra, A.A., Bhattacharya, G., Mukherjee, S., Bose, N., 2014. Near N-S paleo extension in the western Deccan region in India: Does it link strike-slip tectonics with India-Seychelles rifting? *International Journal of Earth Sciences* 1645–1680.
- Misra, A.A., Sinha, N., Mukherjee, S., 2015. Repeat ridge jumps and microcontinent separation: insights from NE Arabian Sea. *Marine and Petroleum Geology* 59, 406–428.
- Mooney, W., Beroza, G., Kind, R., 2007. Fault zones from top to bottom. In: Handy, M.R., Hirth, G., Hovius, N. (Eds.), *Tectonic Faults - Agents of Change on a Dynamic Earth*. Dahlem Workshop Report 95. The MIT Press, Cambridge, Mass., USA, pp. 2–46.
- Mukherjee, S., 2010a. Structures at meso- and micro-scales in the Sutlej section of the Higher Himalayan Shear Zone in Himalaya. *e-Terra* 7, 1–27.
- Mukherjee, S., 2010b. Microstructures of the Zaskar shear zone. *Earth Science India* 3, 9–27.

- Mukherjee, S., 2012a. Tectonic implications and morphology of trapezoidal mica grains from the Sutlej section of the Higher Himalayan Shear Zone, Indian Himalaya. *The Journal of Geology* 120, 575–590.
- Mukherjee, S., 2012b. A microduplex. *International Journal of Earth Sciences* 101, 503.
- Mukherjee, S., 2013a. *Deformation Microstructures in Rocks*. Springer.
- Mukherjee, S., 2013b. Higher Himalaya in the Bhagirathi section (NW Himalaya, India): its structures, backthrusts and extrusion mechanism by both channel flow and critical taper mechanism. *International Journal of Earth Sciences* 102, 1851–1870.
- Mukherjee, S., 2013c. Channel flow extrusion model to constrain dynamic viscosity and Prandtl number of Higher Himalayan Shear Zone. *International Journal of Earth Sciences* 102, 1811–1835.
- Mukherjee, S., 2014a. *Atlas of Shear Zone Structures in Meso-scale*. Springer.
- Mukherjee, S., 2014b. Review of flanking structures in meso- and micro-scales. *Geological Magazine* 151, 957–974.
- Mukherjee, S., A review on out-of-sequence deformation in the Himalaya. In: Mukherjee, S., Carosi, R., van der Beek, P., Mukherjee, B.K., Robinson, D. (Eds.), *Tectonics of the Himalaya*. Geological Society, London. Special Publication 412 (in press).
- Mukherjee, S., Koyi, H.A., 2010a. Higher Himalayan Shear Zone, Sutlej section: structural geology and extrusion mechanism by combination of simple shear, pure shear and channel flow in shifting modes. *International Journal of Earth Sciences* 99, 1267–1303.
- Mukherjee, S., Koyi, H.A., 2010b. Higher Himalayan Shear Zone: Zaskar Indian Himalaya-Microstructural studies and extrusion mechanism by a combination of simple shear and channel flow. *International Journal of Earth Sciences* 99, 1267–1303.
- Navabpour, P., Angelier, J., Barrier, E., 2007. Cenozoic post-collisional brittle tectonic history and stress reorientation in the High Zagros Belt (Iran, Fars Province). *Tectonophysics* 432, 101–131.
- Novakova, L., 2010. Detailed brittle tectonic analysis of the limestones in the quarries near Vápenná village. *Acta Geodynamica et Geomaterialia* 7, 1–8.
- Novakova, L., 2014. Evolution of paleostress fields and brittle deformation in Hronov-Poříčí Fault Zone. Bohemian Massif. *Studia Geophysica et Geodaetica* 58, 269–288.
- Passchier, C.W., Trouw, R.A.J., 2005. *Microtectonics*. Springer, Berlin. 371 pp.
- Pease, V., Argent, J., 1999. The northern Sacramento mountains, SW United States, Part I: structural profile through a crustal extensional detachment system. In: MacNiocaill, C., Ryan, P. (Eds.). *Continental Tectonics*, vol. 164. Geological Society of London Special Publication, pp. 179–198.
- Pease, V., Foster, D., Wooden, J., O’Sullivan, P., Argent, J., Fanning, C., 1999. The northern Sacramento mountains, SW United States, Part II: exhumation history and detachment faulting. In: MacNiocaill, C., Ryan, P. (Eds.). *Continental Tectonics*, vol. 164. Geological Society of London Special Publication, pp. 199–237.
- Petit, J.P., 1987. Criteria for the sense of movement on fault surfaces in brittle rocks. *Journal of Structural Geology* 9, 597–608.
- Placer, L., Vrabec, M., Celarc, B., 2010. The bases for understanding of the NW Dinarides and Istria Peninsula tectonics. *Geologija* 53, 55–86.
- Polino, R., Dal Piaz, G.V., Gosso, G., 1990. Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps. *Mémoires. Société Géologique France* 156, 345–367.
- Poljak, M., Živčić, M., Zupančič, P., 2000. The seismotectonic characteristics of Slovenia. *Pure and Applied Geophysics* 157, 37–55.
- Price, N.A., Johnson, S.E., Gerbi, C.C., West Jr., D.P., 2012. Identifying deformed pseudotachylyte and its influence on the strength and evolution of a crustal shear zone at the base of the seismogenic zone. *Tectonophysics* 518–521, 63–83. <http://dx.doi.org/10.1016/j.tecto.2011.11.011>.
- Ramsay, J.G., Huber, R., 1983. *The techniques of modern structural geology. Strain Analysis*, vol. 1, Academic Press, New York, NY, p. 307.
- Rattenbury, M.S., Townsend, D.B., Johnston, M.R., 2006. *Geology of the Kaikoura Area. Scale 1:250 000*. GNS Science, Lower Hutt, New Zealand.
- Ravna, E.J.K., Andersen, T.B., Jolivet, L., De Capitani, C., 2010. Cold subduction and the formation of lawsonite/eclogite – constraints from prograde evolution of eclogitized pillow lava from Corsica. *Journal of Metamorphic Geology* 28, 381–395.
- Rykkelid, E., Fossen, H., 2002. Layer rotation around vertical fault overlap zones: observations from seismic data, field examples, and physical experiments. *Marine and Petroleum Geology* 19, 181–192.
- Sasvári, Á., Csontos, L., Palotai, M., 2009. Structural geological observations in tölgyhát quarry (Gerecse mts., Hungary). *Földtani Közlöny* 139, 55–66.
- Sibson, R.H., Toy, V.G., 2006. The habit of fault-generated pseudotachylyte: Presence vs. absence of friction-melt. In: *Earthquakes: Radiated energy and the physics of faulting*. Geophysical Monograph Series 170, 153–166.
- Simpson, C., 1985. Deformation of granitic rocks across the brittle-ductile transition. *Journal of Structural Geology* 7, 503–511.
- Shimamoto, T., Togo, T., 2012. Earthquakes in the lab. *Science* 338, 54–55.
- Sibson, R.H., 1975. Generation of pseudotachylyte by ancient seismic faulting. *Geophysical Journal International* 43, 775–794.
- Smyth, J.R., 1980. Cation vacancies and the crystal chemistry of breakdown reactions in kimberlitic omphacites. *American Mineralogist* 65, 1185–1191.
- Špaček, P., Sýkorová, Z., Pazdírková, J., Švancara, J., Havří, J., 2006. Present-day seismicity of the south-eastern Elbe Fault System (NE Bohemian Massif). *Studia Geophysica et Geodaetica* 50, 233–258.
- Spray, J., 1992. A physical basis for the frictional melting of some rock-forming minerals. *Tectonophysics* 204, 201–221.
- Srivastava, D.C., John, G., 1999. Deformation in the Himalayan Frontal Fault Zone: evidence from small-scale structures in Mohand-Khara area, NW Himalaya. In: Jain, A.K., Manickavasagam (Eds.), *Geodynamics of the NW Himalaya*. Gondwana Research Group Memoir, pp. 273–284.
- Swanson, M., 1992. Fault structure, wear mechanisms and rupture processes in pseudotachylyte generation. *Tectonophysics* 204, 223–242.
- Tari, G., 1994. *Alpine Tectonics of the Pannonian Basin* (Ph.D. thesis). Rice University, Texas, USA, 501 p.
- Tavarnelli, E., 1999. Normal faults in thrust sheets: pre-orogenic extension, post-orogenic extension, or both? *Journal of Structural Geology* 21, 1011–1018.
- Teisseyre, H., 1959. Einige Bemerkungen über die Methodik der Mikrostrukturen in der tektonischen Forschung, *Freiberger Forsch., Hft.*, c.57.
- Tjia, H.D., 1964. Slickensides and fault movements. *Geological Society of America Bulletin*. 75, 683–686.

- Togo, T., Shimamoto, T., 2012. Energy partition for grain crushing in quartz gouge during subseismic to seismic fault motion: an experimental study. *Journal of Structural Geology* 38, 139–155.
- Törő, B., Pratt, B.R., Renaut, R.W., 2013. Paleoseismic indicators in the lacustrine Green river formation (Eocene, USA) – characteristics and implications. *Geological Society of America Abstracts with Programs* 45, 357.
- Tullis, T.E., Bürgmann, R., Cocco, M., Hirth, G., King, G.C.P., Oncken, O., Otsuki, K., Rice, J.R., Rubin, A., Segall, P., Shapiro, S.A., Wibberley, C.A.J., 2007. Group report: Rheology of fault rocks and their surroundings. In: Handy, M.R., Hirth, G., Hovius, N. (Eds.), *Tectonic Faults - Agents of Change on a Dynamic Earth*. Dahlem Workshop Report 95. The MIT Press, Cambridge, Mass., USA, pp. 183–204.
- Valenta, J., Gazdova, R., Kolinsky, P., 2011. Seismo-hydrological monitoring in the area of the Hronov-Porčí fault zone, northern Czech Republic, Central Europe. *American Geophysical Union. Fall Meeting 2011*, S11B–S2211.
- Vanossi, M., Cortesogno, L., Galbiati, B., Messiga, B., Piccardo, G., Vannucci, R., 1984. *Geologia delle Alpi Liguri: dati, problemi, ipotesi*. Memorie della Società Geologica Italiana 28, 5–75.
- Vignaroli, G., Rossetti, F., Belardi, G., Billi, A., 2011. Linking rock fabric to fibrous mineralisation: a basic tool for the asbestos hazard. *Natural Hazards and Earth Science Systems* 11, 1267–1280.
- Vignaroli, G., Rossetti, F., Rubatto, D., Theye, T., Lisker, F., Phillips, D., 2010. Pressure-Temperature-Deformation-time (P-T-d-t) exhumation history of the Voltri Massif HP-complex, Ligurian Alps, Italy. *Tectonics* 29, TC6009.
- Woldřich, J.N., 1901. Earthquake in the north-eastern Bohemia on January 10, 1901 [in Czech]. *Transaction of the Academic Sciences of the Czech Republic, Series II* 10, 1–33.
- World Health Organization, 1986. *Asbestos and Other Natural Mineral Fibres*. Environmental Health Criteria, Geneva. No. 53.
- Yao, L., Shimamoto, T., Ma, S., Han, R., Mizoguchi, K., 2013. Rapid postseismic strength recovery of Pingxi fault gouge from the Longmenshan fault system: experiments and implications for the mechanisms of high-velocity weakening of faults. *Journal of Geophysical Research* 118, 1–17, <http://dx.doi.org/10.1002/jgrb.50308>.

Chapter 4

Boudins and Mullions

KEYWORDS

Boudins; Mullions; Pinch and swell structures; Scar folds.

Local brittle–ductile extension partially or completely separate clasts. These segmented clasts are called boudins. Asymmetric boudins can be used to decipher shear sense (Goscombe et al., 2004). See Abe et al. (2013) for fracture patterns in boudinage. Mullions are *linear fluted structures developed within a rock or at lithological interfaces* (Twiss and Moores, 2007). Depending on their geneses, Twiss and Moores (2007) classified them into three types: “fold mullion,” “fault mullion,” and “irregular mullion.” Viscosity contrast between the boudinaged/mullion material and the host rock is one of the controlling factors of their geometries (Sokoutis, 1990; Talbot, 1999; Schmalholz et al., 2008; Schmalholz and Maeder, 2012). Maeder et al. (2009) used the term “segment structure” to describe boudins and mullions together (Figs. 4.1–4.18). Mukherjee (2014a,b) reviewed terms to describe boudins in the light of flanking structures.

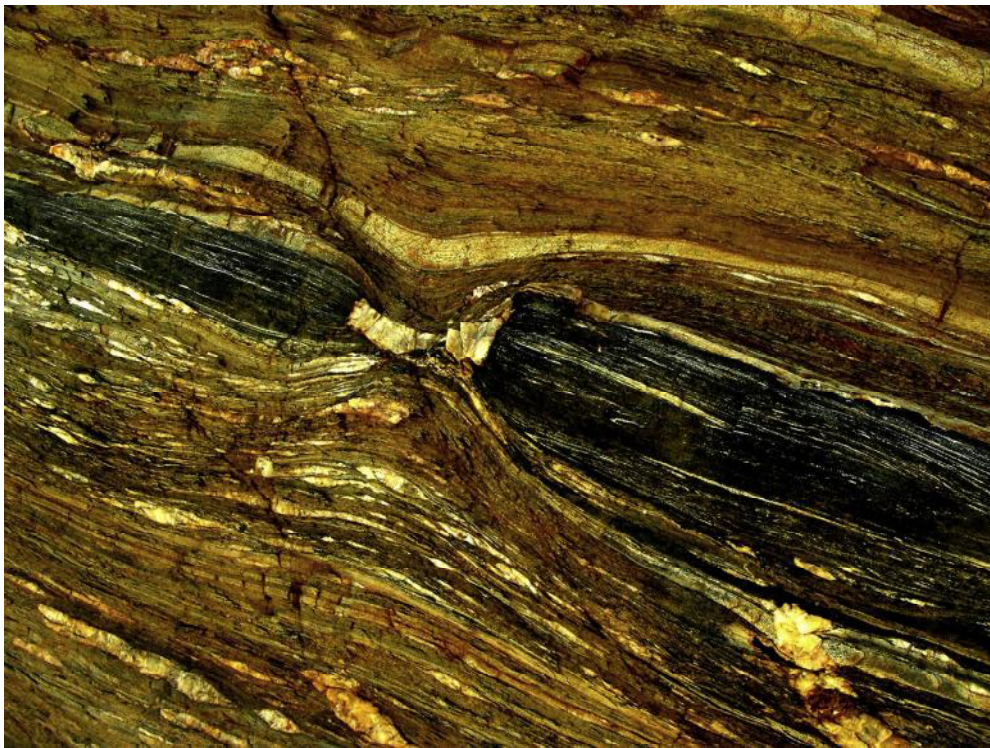


FIGURE 4.1 Photograph from the Gaub Canyon, Namibia, showing a boudinaged metabasalt layer enveloped by metaturbidites in the Southern Marginal Zone of the Damara Belt. The rocks deformed during Neoproterozoic to Cambrian, Pan African assembly of Gondwana (e.g., Barnes and Sawyer, 1980), with peak metamorphic conditions in the amphibolite facies. The rock assemblage comprises metamorphosed basalt, sandstone, mudstone, and chert, which represent intercalated continental and oceanic materials that were likely deformed in an accretionary prism (Kukla and Stanistreet, 1991). The photo highlights the rheological contrasts that develop through intercalation of lithologies of variable viscosity. In this case, the basaltic layer has fractured in the boudin neck, allowing formation of a quartz vein, whereas metasediments are locally folded to fill the gap between boudins of metabasalt. This provides an example of mixed brittle–viscous deformation at temperatures in excess of the brittle to viscous transition in quartzofeldspathic rocks, and a possible geological analogue to the mixture of transient creep and episodic brittle failure inferred to be responsible for deep tremor and slow slip in active subduction zones (Fagereng et al., 2014). Photo width: ~2 m. (Ake Fagereng)

REFERENCES

- Abe, S., Ural, J., Kettermann, M., 2013. Fracture patterns in nonplane strain boudinage—insights from 3-D discrete element models. *Journal of Geophysical Research: Solid Earth* 118, 1304–1315.
- Barnes, S., Sawyer, E., 1980. An alternative model for the Damara mobile belt: Ocean crust subduction and continental convergence. *Precambrian Research* 13, 297–336.
- Christensen, Nikolas I., Lundquist, Susan M., 1982. Pyroxene orientation within the upper mantle. *The Geological Journal of America Bulletin* 93, 282.
- Fagereng, A., Hillary, G.W.B., Diener, J.F.A., 2014. Brittle-viscous deformation, slow slip, and tremor. *Geophysical Research Letters* 41, 4159–4167.
- Fossen, H., 2010. *Structural Geology*. Cambridge University Press, New York.
- Ghosh, S.K., 1993. *Structural Geology: Fundamentals and Modern Developments*. Pergamon Press, Oxford. 598 pp.
- Ghosh, S.K., Sengupta, S., 1999. Boudinage and composite boudinage in superposed deformation and migmatization. *Journal of Structural Geology* 21, 97–110.
- Goscombe, B.D., Passchier, C.W., 2003. Asymmetric boudins as shear sense indicators—an assessment from field data. *Journal of Structural Geology* 25, 575–589.
- Goscombe, B.D., Passchier, C.W., Hand, M., 2004. Boudinage classification, end member boudin types and modified boudin structures. *Journal of Structural Geology* 26, 739–763.
- Kukla, P.A., Stanistreet, I.G., 1991. Record of the Damaran Khomas Hochland accretionary prism in central Namibia: refutation of an “ensialic” origin of a Late Proterozoic orogenic belt. *Geology* 19, 473–476.
- Maeder, X., Passchier, C.W., Koehn, D., 2009. Modelling of segment structures: boudins, bone-boudins, mullions and related single- and multiphase deformation features. *Journal of Structural Geology* 31, 817–830.
- Mukherjee, S., 2010a. Microstructures of the Zaskar Shear Zone. *Earth Science India* 3, 9–27.
- Mukherjee, S., 2010b. Structures at meso- and micro-scales in the Sulej section of the Higher Himalayan Shear Zone in Himalaya. *e-Terra* 7, 1–27.
- Mukherjee, S., 2013a. *Deformation Microstructures in Rocks*. Springer.
- Mukherjee, S., 2013b. Higher Himalaya in the Bhagirathi section (NW Himalaya, India): its structures, backthrusts and extrusion mechanism by both channel flow and critical taper mechanism. *International Journal of Earth Sciences* 102, 1851–1870.
- Mukherjee, S., 2014a. Review of flanking structures in meso- and micro-scales. *Geological Magazine* 151, 957–974.
- Mukherjee, S., 2014b. *Atlas of Shear-zone Structures in Meso-scale*. Springer.
- Mukherjee, S., Koyi, H.A., 2010a. Higher Himalayan Shear Zone, Zaskar Indian Himalaya-microstructural studies and extrusion mechanism by combination of simple shear and channel flow. *International Journal of Earth Sciences* 99, 1083–1110.
- Mukherjee, Koyi, 2010b. Higher Himalayan Shear Zone, Sulej section: structural geology and extrusion mechanism by combination of simple shear, pure shear and channel flow in shifting modes. *International Journal of Earth Sciences* 99, 1267–1303.
- Schefer, S., Egli, D., Missoni, S., Bernoulli, D., Fügenschuh, B., Gawlick, H.-J., Jovanović, D., Krystyn, L., Lein, R., Schmid, S.M., Sudar, M., 2010. Triassic metasediments in the internal Dinarides (Kopaonik area, southern Serbia): stratigraphy, paleogeographic and tectonic significance. *Geologica Carpathica* 61, 89–109.
- Schmalholz, S.M., Maeder, X., 2012. Pinch-and-swell structure and shear zones in viscoplastic layers. *Journal of Structural Geology* 37, 75–88.
- Schmalholz, S.M., Schmid, D.W., Fletcher, R.C., 2008. Evolution of pinch-and-swell structures in a power-law layer. *Journal of Structural Geology* 30, 649–663.
- Sokoutis, D., 1990. Experimental mullions at single and double interfaces. *Journal of Structural Geology* 12, 365–373.
- Talbot, C.J., 1999. Can field data constrain rock viscosities? *Journal of Structural Geology* 21, 949–957.
- Twiss, R.J., Moores, E.M., 2007. *Structural Geology*, second ed. W. H. Freeman and Company, New York. 313 pp.

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FIGURE 5.8 Quartz vein network defined mainly by two sets of veins. The set of veins dipping toward left are usually thicker than that dipping toward right. Chitradurga district, Karnataka, India. (Aabha Singh)

REFERENCES

- Bons, P.D., Elburg, M.A., Gomez-Rivas, E., 2012. A review of the formation of tectonic veins and their microstructures. *Journal of Structural Geology* 43, 33–62.
- Davis, G.H., Reynolds, S.J., 1996. *Structural Geology of Rocks and Regions*, second ed. John Wiley & Sons, Inc.
- Davis, G.H., Reynolds, S.J., Kluth, C.F., 2012. *Structural Geology of Rocks and Regions*, third ed. John Wiley & Sons. 839p.
- Fossen, H.A., 2010. *Structural Geology*. Cambridge University Press. pp. 122–123.
- Hilgers, C., Kirschner, D., Breton, J.-P., Urai, J.L., 2006. Fracture sealing and fluid overpressures in limestones of the Jabel Akhbar Dome, Oman Mountains. *Geofluids* 6, 168–184.
- Holland, M., Urai, J.L., 2010. Evolution of anastomosing crack–seal vein networks in limestones: insight from an exhumed high-pressure cell, Jabal Shams, Oman Mountains. *Journal of Structural Geology* 32, 1279–1290.
- Holland, M., Urai, J.L., Muechez, P., Willemsse, J.M., 2009a. Evolution of fractures in a highly dynamic thermal, hydraulic, and mechanical system; (I), Field observations in Mesozoic carbonates, Jabal Shams, Oman Mountains. *GeoArabia* 14, 57–110.
- Holland, M., Saxena, N., Urai, J.L., 2009b. Evolution of fractures in a highly dynamic thermal, hydraulic, and mechanical system—(ii) remote sensing fracture analysis, Jabal Shams, Oman Mountains. *GeoArabia* 14, 163–194.
- Maeder, 2014. Complex vein systems as a data source in tectonics: An example from the Ugab valley, NW Namibia. *Journal of Structural Geology* 62, 125–140.
- Mukherjee, S., 2007. *Geodynamics, Deformation and Mathematical Analysis of Metamorphic Belts of the NW Himalaya*. (Unpublished Ph.D. thesis). Indian Institute of Technology Roorkee, pp.1–267.
- Mukherjee, S., 2010. Structures in meso- and micro-scales in the Sutlej section of the Higher Himalayan Shear Zone, Indian Himalaya. *e-Terra* 7, 1–27.
- Mukherjee, S., 2010a. Structures at Meso- and Micro-scales in the Sutlej section of the Higher Himalayan Shear Zone in Himalaya. *e-Terra* 7, 1–27.
- Mukherjee, S., 2013a. Higher Himalaya in the Bhagirathi section (NW Himalaya, India): its structures, backthrusts and extrusion mechanism by both channel flow and critical taper mechanism. *International Journal of Earth Sciences* 102, 1851–1870.
- Mukherjee, S., 2013b. Channel flow extrusion model to constrain dynamic viscosity and Prandtl number of Higher Himalayan Shear Zone. *International Journal of Earth Sciences* 102, 1811–1835.
- Mukherjee, S., 2014. *Atlas of Shear Zone Structures in Meso-scale*. Springer.
- Mukherjee, S., Koyi, H.A., 2010a. Higher Himalayan Shear Zone, Sutlej section: structural geology and extrusion mechanism by various combination of simple shear, pure shear and channel flow in shifting modes. *International Journal of Earth Sciences* 99, 1267–1303.

- Novak, M., 2007. Depositional environment of upper carboniferous—lower permian beds in the Karavanke mountains (Southern Alps, Slovenia). *Geologija* 50, 247–268.
- Passchier, C.W., Trouw, R.A.J., 2005. *Microtectonics*, second ed. Springer.
- Virgo, S., Abe, S., Urai, J.L., 2013. Extension fracture propagation in rocks with veins: insight into the crack-seal process using Discrete Element Method modeling. *Journal of Geophysical Research: Solid Earth* 118, 5236–5251.

Chapter 6

Various Structures

KEYWORDS

Columnar joints; Crater; Fissures; Fractures; Pull apart structure; Spheroidal weathering; Xenoliths.

This chapter presents various structures some of which are not worked intensely by structural geologists. Grain boundary migration in rocks observed under optical microscope can constrain the temperature the rock underwent (Stipp et al., 2002). Stability of buildings and fracturing during earthquakes has been a research topic to geoscientists (Krishnan et al., 2006). Study of faults and other structures has helped geoscientists to paleohydrology (Treiman, 2008) (Figures 6.1–6.60).



FIGURE 6.1 Columnar joints, colonnade and entablature. Thick solidifying lava flows develop contraction fractures that propagate from their cooling margins toward hotter interiors. These fractures, called columnar joints, divide a lava flow into columns, with polygonal (ideally hexagonal) shapes in plan. A subhorizontal basaltic lava flow of the Talisker Bay Group, Isle of Skye, Scotland is shown in the figure. The lower part of the flow shows well-developed vertical columns, suggesting nearly horizontal isotherms (contours of constant temperature within the lava flow). Such a columnar tier is called a colonnade. The upper part of this flow shows a highly chaotic and distorted internal structure, as would develop during rainfall or stream flow supplying water into the cooling flow interior and disturbing isotherms. This tier is known as an entablature. The colonnade and the entablature, though with greatly different field appearance, are part of a single lava flow. Here, the combined thickness of both is 120 m. (Hetu Sheth)

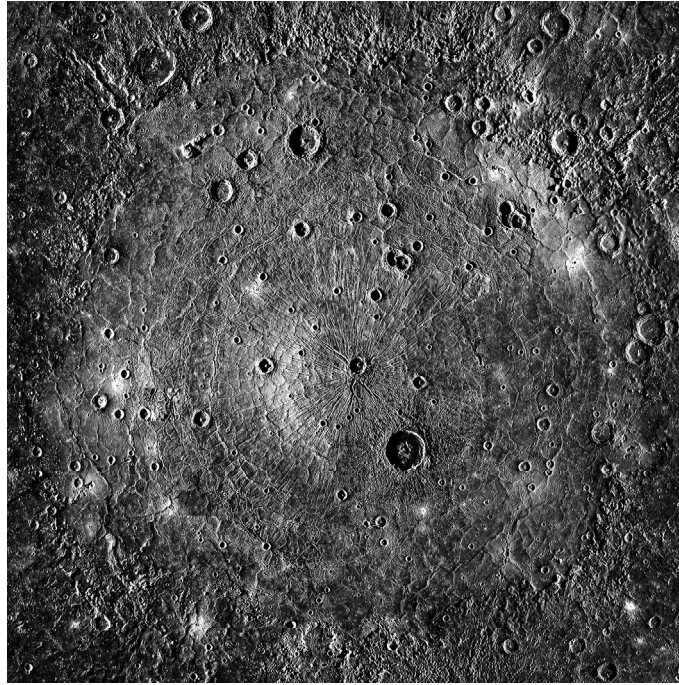


FIGURE 6.60 The Caloris basin is the largest preserved impact structure on Mercury. With an E–W diameter of 1640 km, the floor of the basin subtends $\sim 40^\circ$ of arc. The interior of the basin, which has been filled with voluminous, low-viscosity lavas, is replete with both contractional (wrinkle ridges) and extensional (graben) structures. The origin of these structures is not clear. The graben may have formed by thermal contraction of the interior lavas, similar to what is observed within Goethe basin, for example. Yet the pronounced radial orientations of the innermost graben are yet to be explained. The wrinkle ridges may be the result of subsidence of the Caloris interior lavas; however, in many places they remained active after the graben, and so could be due to the sustained global contraction of Mercury as its interior cooled. The image is in an orthographic projection centered at 31.5°N , 162.7°E . (Image credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington). (Christian Klimczak, Paul K. Byrne)

REFERENCES

- Barker, A.J., 1998. Introduction to Metamorphic Textures and Microstructures, second ed. Blackie, Glasgow. p. 264.
- Bikramaditya Singh, R.K., Gururajan, N.S., 2011. Microstructures in quartz and feldspars of the Bomdila gneiss from western Arunachal Himalaya, India: implications for geotectonic evolution of the Bomdila mylonitic zone. *Journal of Asian Earth Sciences* 42, 1163–1178.
- Bons, P.D., Urai, J.L., 1992. Syndeformational grain growth: microstructures kinetics. *Journal of Structural Geology* 14, 1101–1109.
- Bottjer, D., Hegadorn, J.W., 2007. In: Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., Catuneau, O. (Eds.), *Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record*. Elsevier, pp. 53–71.
- Brodie, K.H., Rutter, E.H., 1985. On the relationship between deformation and metamorphism, with special reference to the behavior of basic rocks. In: Thompson, A., Ruby, D. (Eds.), *Metamorphic Reactions: Kinetics, Textures, and Deformation*. Springer, pp. 138–179.
- Brogi, A., Capezzuoli, E., 2009. Travertine deposition and faulting: the fault-related travertine fissure-ridge at Terme S. Giovanni, Rapolano Terme (Italy). *International Journal of Earth Sciences* 98, 931–947.
- Chesterman, C.W., Kleinhampl, F.J., 1991. Travertine hot springs, Mono County, California. *California Geology* 44, 171–182.
- Choukroune, P., Séguret, M., 1973. Carte structurale des Pyrénées, 1/500.000, Université de Montpellier–ELF. Aquitaine.
- Christie, J.M., Griggs, D.T., Carter, B.J., 1964. Experimental evidence of basal slip in quartz. *Journal of Geology* 72, 734–756.
- Crowe, W.A., Osanai, Y., Toyoshima, T., Owada, M., Tsunogae, T., Hokada, T., 2002. SHRIMP geochronology of a mylonite zone on Tonagh island: characterization of the last high-grade tectonothermal event in the Napier complex, East Antarctica. *Polar Geoscience* 15, 17–36.
- Crossey, L.J., Karlstrom, K.E., 2012. Travertines and travertine springs in eastern Grand Canyon: what they tell us about groundwater, paleoclimate, and incision of Grand Canyon. *Geological Society of America Special Papers* 489, 131–143.
- Davis, G.H., Reynolds, S.J., Kluth, C.F., 2012. *Structural Geology of Rocks and Regions*, third edition. Wiley, New York.
- De Filippis, L., Billi, A., 2012. Morphotectonics of fissure ridge travertines from geothermal areas of Mammoth Hot Springs (Wyoming) and Bridgeport (California). *Tectonophysics* 548–549, 34–48.
- De Filippis, L., Faccenna, C., Billi, A., Anzalone, E., Brilli, M., Özkul, M., Soligo, M., Tuccimei, P., Villa, I., 2012. Growth of fissure ridge travertines from geothermal springs of Denizli basin, western Turkey. *Geological Society America Bulletin* 124, 1629–1645.
- De Filippis, L., Faccenna, C., Billi, A., Anzalone, E., Brilli, M., Soligo, M., Tuccimei, P., 2013. Plateau versus fissure ridge travertines from quaternary geothermal springs of Italy and Turkey: interactions and feedbacks between fluid discharge, paleoclimate, and tectonics. *Earth-Science Reviews* 123, 35–52.

- Denyer, P., Alvarado, G.E., 2007. Mapa geológico de Costa Rica. Escala 1:400.000. Librería Francesa, San José, Costa Rica.
- Derez, T., Pennock, G., Drury, M., Sintubin, M., 2015. Low-temperature intracrystalline deformation microstructures in quartz. *Journal of Structural Geology* 71, 3–23.
- Dillon, J.T., Brosge, W.P., Dutro, J.T., 1986. Generalized Geologic Map of the Wiseman Quadrangle. US Geological Survey Open-File Report 86-219, Alaska.
- Eriksson, P.G., Porada, H., Banerjee, S., Bouougri, E., Sarkar, S., Bumby, A.J., 2007. In: Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., Catuneau, O. (Eds.), *Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record*. Elsevier, pp. 76–105.
- Faccenna, C., Soligo, M., Billi, A., De Filippis, L., Funicello, R., Rossetti, C., Tuccimei, P., 2008. Late Pleistocene depositional cycles of the Lapis Tiburtinus travertine (Tivoli, central Italy): possible influence of climate and fault activity. *Global and Planetary Change* 63, 299–308.
- Fagereng, A., 2011. Frequency-size distribution of competent lenses in a block-in-matrix melange: imposed length scales of brittle deformation? *Journal of Geophysical Research* 116, B05302.
- French, B.M., Koeberl, C., 2010. The convincing identification of terrestrial meteorite impact structures: what works, what doesn't, and why. *Earth-Science Reviews* 98, 123–170.
- Frid, V., Bahat, D., Rabinovich, A., 2005. Analysis of en echelon/hackle fringes and longitudinal splits in twist failed glass samples by means of fractography and electromagnetic radiation. *Journal of Structural Geology* 27, 145–159.
- Fujimoto, Y., Yamamoto, M., 2010. On the granitoids in the Shirakami mountains and correlation to the Cretaceous to Paleogene granitoids distributed in the Northeast Japan. *Earth Science* 64, 127–144. In Japanese with English abstract.
- Gay, N.C., 1974. Modification of deformation lamellae during brittle-ductile deformation of quartzite. *Geological Society of America Bulletin* 85, 1237–1242.
- Gehrels, G.E., DeCelles, P.G., Ojha, T.P., Upreti, B.N., 2006. Geologic and U-Th-Pb geochronologic evidence for early Paleozoic tectonism in the Kathmandu thrust sheet, central Nepal Himalaya. *Geological Society of America Bulletin* 118, 185–198.
- Gratier, J.-P., Frery, E., Deschamps, P., Røyne, A., Renard, F., Dysthe, D., Ellouz-Zimmerman, N., Hamelin, B., 2012. How travertine veins grow from top to bottom and lift the rocks above them: the effect of crystallization force. *Geology* 40, 1015–1018.
- Grützner, C., Reicherter, K., Hübscher, C., Silva, P.G., 2012. Active faulting and neotectonics in the Baelo Claudia area, Campo de Gibraltar (southern Spain). *Tectonophysics* 554–557, 127–142.
- Hamers, M.F., Drury, M.R., 2011. Scanning electron microscope-cathodoluminescence (SEM-CL) imaging of planar deformation features and tectonic deformation lamellae in quartz. *Meteorites & Planetary Science* 46, 1814–1831.
- Hancock, P.L., Chalmers, R.M.L., Altunel, E., Çakir, Z., 1999. Travertines: using travertine in active fault studies. *Journal of Structural Geology* 21, 903–916.
- Hefferan, K., O'Brien, J., 2010. *Earth Materials*. John Wiley & Sons Ltd, Wiley-Blackwell, UK.
- Hobbs, B.E., Means, W.D., Williams, P.F., 1976. *An Outline of Structural Geology*. John Wiley & Sons.
- Hurst, A., Scott, A., Vigorito, M., 2011. Physical characteristics of sand injectites. *Earth-Science. Reviews* 106, 215–246.
- Knauth, L.P., 1979. A model for the origin of chert in limestone. *Geology* 7, 274–277.
- Kamai, R., Hatzor, Y.H., 2008. Numerical analysis of block stone displacements in ancient masonry structures: a new method to estimate historic ground motions. *International Journal for Numerical and Analytical Methods in Geomechanics* 32, 1321–1340.
- Kamh, G.M.E., Kallash, A., Azzam, R., 2008. Factors controlling building susceptibility to earthquakes: 14-year recordings of Islamic archaeological sites in old Cairo, Egypt: a case study. *Environmental Geology* 56, 269–279.
- Karakhanian, A.S., Trifonov, V.G., Ivanova, T.P., Avagyan, A., Rukieh, M., Minini, H., Dodonov, A.E., Bachmanov, D.M., 2008. Seismic deformation in the St. Simeon monasteries (Qal'at Sim'an), northwestern Syria. *Tectonophysics* 453, 122–147.
- Kázmér, M., Damages to ancient buildings from earthquakes. In: Beer M., Patelli E., Kougioumtzoglou I., Au, I.S.-K. (Eds.), *Encyclopedia of Earthquake Engineering*, Springer, Berlin, submitted for publication.
- Kázmér, M., Major, B., 2010. Distinguishing damages of two earthquakes – archeoseismology of a Crusader castle (Al-Marqab citadel, Syria). In: Sintubin, M., Stewart, I., Niemi, T., Altunel, E. (Eds.), *Ancient Earthquakes*, vol. 471. Geological Society of America Special Paper, pp. 186–199.
- Korjenkov, A.M., Mazor, E., 2003. Archeoseismology in Mamshit (Southern Israel): cracking a millennium-old code of earthquakes preserved in ancient ruins. *Archäologischer Anzeiger* 2003 (2), 51–82.
- Korjenkov, A.M., Mazor, E., 1999. Seismogenic origin of the ancient Avdat ruins, Negev desert. *Israel Natural Hazards* 18, 193–226.
- Krishnan, S., Ji, C., Komatitsch, D., Tromp, J., 2006. Case studies of damage to tall steel moment-frame buildings in southern California during large San Andreas earthquakes. *Bulletin of the Seismological Society of America* 96, 1523–1537.
- Kukla, P.A., Stanistreet, I.G., 1991. Record of the Damaran Khomas Hochland accretionary prism in central Namibia: Refutation of an "Ensialic" origin of a Late Proterozoic orogenic belt. *Geology* 19, 473–476.
- Ludman, A., West, Jr., D.P., (Eds.). 1999. The Norumbega fault system of the northern Appalachians. *Geological Society of America Special Paper* 331, 199.
- Marco, S., 2008. Recognition of earthquake-related damage in archaeological sites: examples from the Dead Sea fault zone. *Tectonophysics* 453, 148–156.
- Meghraoui, M., Gomez, F., Sbeinati, R., Van der Woerd, J., Mouty, M., Darkal, A.N., Radwan, Y., Layyous, I., Al Najjar, H., Darawch, R., Hijazi, F., Al-Ghazzi, R., Barazangi, M., 2003. Evidence for 830 years of seismic quiescence from paleoseismology, archeoseismology and historical seismicity along the Dead Sea Fault in Syria. *Earth and Planetary Science Letters* 210, 35–52.
- Meneghini, F., Kisters, A., Buick, I., Fagereng, A., 2014. Fingerprints of Late Neoproterozoic Ridge Subduction in the Pan-African. *Geology, Damara belt, Namibia. Geology* 42, 903–906.

- Millán, H., Pocoví, A., Casas, A., 1995. El frente de cabalgamiento surpirenaico en el extremo occidental de las Sierras Exteriores: sistemas imbricados y pliegues de despegue. *Revista de la Sociedad Geológica de España* 8, 73–90.
- Mooney, W., Beroza, G., Kind, R., 2007. Fault zones from top to bottom. In: Handy, M.R., Hirth, G., Hovius, N. (Eds.), *Tectonic Faults - Agents of Change on a Dynamic Earth*. The MIT Press, Cambridge, Mass., USA, pp. 2–46. Dahlem Workshop Report 95.
- Mukherjee, S., 2010. V-pull apart structure in garnet in macro-scale. *Journal of Structural Geology* 32, 605.
- Mukherjee, S., 2012. Simple shear is not so simple! Kinematics and shear senses in Newtonian viscous simple shear zones. *Geological Magazine* 149, 819–826.
- Mukherjee, S., 2013. *Deformation Microstructures in Rocks*. Springer.
- Mukherjee, S., 2014. *Atlas of Shear Zone Structures in Meso-scale*. Springer.
- Muñoz, J.A., Beamud, E., Fernández, O., Arbués, P., Dinarès-Turell, J., Poblet, J., 2013. The Ainsa fold and thrust oblique zone of the central Pyrenees: kinematics of a curved contractional system from paleomagnetic and structural data. *Tectonics* 32, 1142–1175.
- Nichols, G.J., 1987. The Structure and Stratigraphy of the Western External Sierras of the Pyrenees, Northern Spain. *Geological Journal* 22, 245–259.
- Novakova, L., 2008. Main directions of the fractures in the limestone and granite quarries along the Sudetic Marginal Fault near Vápenná village, NE Bohemian Massif, Czech Republic. *Acta Geodynamica et Geomaterialia* 5, 49–55.
- Novakova, L., Hájek, P., Šťastný, M., 2010. Determining the relative age of fault activity through analyses of gouge mineralogy and geochemistry: a case study from Vápenná (Rychlebské hory Mts.), Czech Republic. *International Journal of Geosciences* 1, 66–69.
- Oliva-Urcia, B., Casas, A.M., Pueyo, E.L., Pocoví, A., 2012a. Structural and paleomagnetic evidence for non-rotational kinematics in the western termination of the External Sierras (southwestern central Pyrenees). *Geologica Acta* 10, 1–22.
- Osanaí, Y., Nogi, Y., Baba, S., Nakano, N., Adachi, T., Hokada, T., Toyoshima, T., Owada, M., 2013. Geologic evolution of the Sør Rondane Mountains, East Antarctica: collision tectonics proposed based on metamorphic processes and magnetic anomalies. *Precambrian Research* 234, 8–29.
- Owada, M., Osanaí, Y., Tsunogae, T., Hamamoto, T., Kagami, H., Toyoshima, T., Hokada, T., 2001. Sm-Nd garnet ages of retrograde garnet bearing granulites from Tonagh Island in the Napier Complex, East Antarctica: a preliminary study. *Polar Geoscience* 14, 75–87.
- Pease, V., Argent, J., 1999. The northern Sacramento mountains, SW United States, Part I: structural profile through a crustal extensional detachment system. In: MacNiocaill, C., Ryan, P. (Eds.), *Continental Tectonics*, vol. 164. Geological Society of London Special Publication, pp. 179–198.
- Pease, V., Foster, D., Wooden, J., O'Sullivan, P., Argent, J., Fanning, C., 1999. The northern Sacramento mountains, SW United States, Part II: exhumation history and detachment faulting. In: MacNiocaill, C., Ryan, P. (Eds.), *Continental Tectonics*, vol. 164. Geological Society of London Special Publication, pp. 199–237.
- Pueyo, E.L., Parés, J.M., Millán, H., Pocoví, A., 2003a. Conical folds and apparent rotations in paleomagnetism (a case study in the Pyrenees). *Tectonophysics* 362, 345–366.
- Passchier, C.W., Trouw, R.A.J., 2005. *Microtectonics*. Springer-Verlag, Berlin.
- Pau, A., Vestroni, F., 2008. Vibration analysis and dynamic characterization of the Colosseum. *Structural Control and Health Monitoring* 15, 1105–1121.
- Price, N.A., Johnson, S.E., Gerbi, C.C., West Jr., D.P., 2012. Identifying deformed pseudotachylite and its influence on the strength and evolution of a crustal shear zone at the base of the seismogenic zone. *Tectonophysics* 518–521, 63–83.
- Ree, J.H., Kwon, S.H., Park, Y., 2001. Pre-tectonic and post-tectonic emplacements of the granitic rocks in the south central Okcheon belt, South Korea: Implications for the timing of strike-slip shearing and thrusting. *Tectonics* 20, 850–867.
- Rhodes, M.K., Malone, D.H., Carroll, A.R., 2007. Sudden desiccation of Lake Gosiute at ~49 Ma: Downstream record of Heart Mountain faulting? *The Mountain Geologist* 44, 1–10.
- Rodríguez-Pascua, M.A., Pérez-López, R., Silva, P.G., Giner-Robles, J.L., Garduño-Monroy, V.H., Reicherter, K., 2011. A comprehensive classification of earthquake archaeological effects (EAE) for archaeoseismology. *Quaternary International* 242, 20–30.
- Samanta, S.K., Mandal, N., Chakraborty, C., 2001. Development of different types of pull-apart microstructures in mylonites: an experimental investigation. *Journal of Structural Geology* 24, 1345–1355.
- Séguret, M., 1972. *Etude tectonique des nappes et séries décollées de la partie centrale du versant sud des Pyrénées* (PhD. thesis). Caractère synsédimentaire, rôle de la compression et de la gravité. University of Montpellier.
- Silva, P.G., Borja, F., Zazo, C., Groy, J.L., Bardají, T., De Luque, L., Lario, J., Dabrio, C.J., 2005. Archaeoseismic record at the ancient Roman city of Baelo Claudia (Cádiz, south Spain). *Tectonophysics* 408, 129–146.
- Sibson, R.H., Toy, V.G., 2006. The habit of fault-generated pseudotachylite: Presence vs. absence of friction-melt. In: *Earthquakes: Radiated Energy and the Physics of Faulting*. Geophysical Monograph Series 170, 153–166.
- Similox-Tohon, D., Sintubin, M., Muchez, P., Verhaert, G., Vanneste, K., Fernandez, M., Vanduycke, S., Vanhaverbeke, H., Waelkens, M., 2006. The identification of an active fault by a multidisciplinary study at the archaeological site of Sagalassos (SW Turkey). *Tectonophysics* 420, 371–397. Erratum: 435, pp. 55–62.
- Simpson, C., 1985. Deformation of granitic rocks across the brittle-ductile transition. *Journal of Structural Geology* 7, 503–511.
- Stipp, M., Stunitz, H., Heilbronner, R., Schmid, S.M., 2002. The eastern Tonale fault zone: a 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700 C. *Journal of Structural Geology* 24, 1861–1884.
- Takahashi, Y., 1999. Reexamination on the northern extension of the Tanagura Tectonic Line, with special reference to the Nihonkoku-Miomote Mylonite Zone. *Structural Geology* 43, 69–78. In Japanese with English abstract.
- Takahashi, Y., 2002. Granitic mylonites situated around the Shirakami Mountains, Northeast Japan. *Earth Science* 56, 215–216. In Japanese.
- Takahashi, Y., Cho, D.L., Kee, W.S., 2010. Timing of mylonitization in the Funatsu Shear Zone within Hida Belt of southwest Japan: Implications for correlation with the shear zones around the Okcheon Belt in the Korean Peninsula. *Gondwana Research* 17, 102–115.

- Tänavsuu-Milkeviciene, K., Sarg, F.J., 2012. Evolution of an organic-rich lake basin – stratigraphy, climate and tectonics: Piceance Creek basin, Eocene Green River Formation. *Sedimentology* 59, 1735–1768.
- Ternet, Y., Baudin, T., Laumonier, B., Barnolas, A., Gil-Peña, I., Martín-Alfageme, S., 2008. Mapa Geológico de los Pirineos a E. 1: 400.000. IGME–BRGM, Madrid-Orleans.
- Till, A.B., Dumoulin, J.A., Harris, A.G., Moore, T.E., Bleick, H.A., Siwiec, B.R., 2008. Bedrock Geologic Map of the Southern Brooks Range, Alaska, and Accompanying Conodont Data. US Geological Survey Open-File Report 2008-1149. 54 pp.
- Törő, B., Pratt, B.R., Renaut, R.W., 2013. Seismically induced soft-sediment deformation structures in the Eocene lacustrine Green River Formation (Wyoming, Utah, Colorado, USA) – a preliminary study. Poster abstract, Calgary. GeoConvention 2013: Integration Calgary. Poster abstract.
- Toyoshima, T., Osanai, Y., Baba, S., Hokada, T., Nakano, N., Adachi, T., Otsubo, M., Ishikawa, M., Nogi, Y., 2013. Sinistral transpressional and extensional tectonics in Dronning Maud Land, East Antarctica, including the Sør Rondane Mountains. *Precambrian Research* 234, 30–46.
- Toyoshima, T., Osanai, Y., Owada, M., Tsunogae, T., Hokada, T., Crowe, W.A., 1999. Deformation of ultrahigh-temperature metamorphic rocks from Tonagh Island in the Napier Complex, East Antarctica. *Polar Geoscience* 12, 29–48.
- Toyoshima, T., Owada, M., Shiraishi, K., 1995. Structural evolution of metamorphic and intrusive rocks from the central part of the Sør Rondane Mountains, East Antarctica. *Proceedings of the NIPR Symposium on Antarctic Geosciences* 8, 75–97.
- Treiman, A.H., 2008. Ancient groundwater flow in the Valles Marineris on Mars inferred from fault trace ridges. *Nature Geoscience* 1, 181–183.
- Trepmann, C.A., Stockhert, B., Dörner, D., Moghadam, R.H., Kuster, M., Roller, K., 2007. Simulating coseismic deformation of quartz in the middle crust and fabric evolution during postseismic stress relaxation — An experimental study. *Tectonophysics* 442, 83–104.
- Tullis, T.E., Bürgmann, R., Cocco, M., Hirth, G., King, G.C.P., Oncken, O., Otsuki, K., Rice, J.R., Rubin, A., Segall, P., Shapiro, S.A., Wibberley, C.A.J., 2007. Group report: rheology of fault rocks and their surroundings. In: Handy, M.R., Hirth, G., Hovius, N. (Eds.), *Tectonic Faults - Agents of Change on a Dynamic Earth*. Dahlem Workshop Report 95. The MIT Press, Cambridge, Mass, USA, pp. 183–204.
- Twiss, R.J., Moores, E.M., 2007. *Structural Geology*. WH Freeman and Company, New York. pp. 43–45.
- Uysal, I.T., Feng, Y., Zhao, J.X., Isik, V., Nuriel, P., Golding, S.D., 2009. Hydrothermal CO₂ degassing in seismically active zones during the Late Quaternary. *Chemical Geology* 265, 442–454.
- Uysal, I.T., Feng, Y., Zhao, J.X., Altunel, E., Weatherley, D., Karabacak, V., Cengiz, O., Golding, S.D., Lawrence, M.G., Collerson, K.D., 2007. U-series dating and geochemical tracing of late Quaternary travertine in co-seismic fissures. *Earth and Planetary Science Letters* 257, 450–462.
- Van Baelen, H., 2010. Dynamics of a progressive vein development during the late-orogenic mixed brittle-ductile destabilisation of a slate belt. Examples of the High-Ardenne slate belt (Herbeumont, Belgium). *Aardkundige Mededelingen* 24, 221p.
- Van Daalen, M., Heilbronner, R., Kunze, K., 1999. Orientation analysis of localized shear deformation in quartz fibres at the brittle–ductile transition. *Tectonophysics* 303, 83–107.
- Van Noten, K., Claes, H., Soete, J., Foubert, A., Özkul, M., Swennen, R., 2013. Fracture networks and strike–slip deformation along reactivated normal faults in quaternary travertine deposits, Denizli Basin, western Turkey. *Tectonophysics* 588, 154–170.
- Vernon, R.H., 2004. *A Practical Guide to Rock Microstructure*. Cambridge University Press.
- Vernooij M.G.C. 2005. *Dynamic Recrystallisation and Microfabric Development in Single Crystals of Quartz during Experimental Deformation* (Unpublished PhD. thesis), Eidgenössische Technische Hochschule, Zürich.
- Yin, A., Dubey, C.S., Kelty, T.K., Webb, A.A.G., Harrison, T.M., Chou, C.Y., Celerier, J., 2010. Geologic correlation of the Himalayan orogeny and Indian craton: Part 2: structural geology, geochronology, and tectonic evolution of the Eastern Himalaya. *Geological Society of America Bulletin* 122, 360–395.

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